Manuscript: essd-2020-156
Original title: Spatially-explicit estimates of global wastewater production, collection, treatment and re-use
Revised title: Country-level and gridded estimates of wastewater production, collection, treatment and re-use
Authors: Edward R. Jones, Michelle T.H. van Vliet, Manzoor Qadir, Marc F. P. Bierkens

Response for the editor

To the editor,

Thank you for consideration publication of this paper in ESSD. Please find our detailed response to the comments of the reviewers and the manuscript including tracked changes below. We also provide line numbers for the substantive text changes in the manuscript. Please note the line numbers refer to the version of the manuscript that includes the tracked changes.

Many thanks.

Response to comments of reviewers

Reviewer #1

General comments from reviewer

The paper by Jones et al. provides a revised and consistent global outlook of the state of wastewater production, collection, treatment and re-use. It uses available country-level wastewater data and regression analyses to estimate information where it is unavailable. The year selected for the country-level data was 2015, and unavailable data were standardized to the same year using relationships with GDP. In addition, the authors downscaled the country-level data to a 5-min resolution grid using return flow data from the global water balance model PCR-GLOBWB. The downscaling was validated using European, US, and some global (yet less in numbers) records of wastewater treatment plants. Validation efforts delivered reasonable model performance indicators, and uncertainties were estimated using a bootstrapping technique.

The final data product provides a gridded map that includes quantities of wastewater production, collection, treatment and re-use at 5-min spatial resolution. Global water quality models and large-scale water assessments have been lacking this type of information in the past, so this paper is clearly a very important addition to the field. As this is a global effort, there are severe constraints regarding data availability and quality. The authors developed (and explained) reasonable approaches to overcome these problems. While some of their methods are based on speculation regarding the relevant processes, the ultimate test of such an approach is the validation of the results. I think the authors did a commendable job in their validation and comparisons, and I do appreciate that they reveal important shortcomings and clearly state that the results must be interpreted with caution. So overall I think this paper presents an excellent global-scale effort to generate an advanced and novel gridded map of wastewater quantities. The manuscript is generally well written and very clearly structured. I strongly recommend its publication. I have a series of mostly minor comments that I list below. They are all written with the intention to further improve the manuscript. I also want to express my thanks to the authors for providing this important dataset to the research community!

We thank the reviewer very much for the insightful comments and suggestions. We are pleased to read that the reviewer is complimentary about the manuscript and recognises the value of our dataset for the research community. The reviewer addresses a number of important topics, which we overall agree with and which have all been addressed in the revised manuscript. Please see our point-by-point responses to the individual comments below.

Individual comments

1. Title (and elsewhere): After reading the title ("Spatially-explicit . . .") my initial expectation was that the paper will describe explicit locations of wastewater production and collection (e.g. locations of wastewater treatment plants). Only when reading the manuscript, I realized that the dataset refers to a modeled distribution of wastewater quantities at sub-national scale. This is still great, but maybe a slightly different title could help avoiding this confusion, such as "Downscaled gridded model estimates of global wastewater. . ." or you could at least refer to "model estimates" rather than just "estimates".

We understand this source of confusion for the reviewer. We have changed the provisional title to: "*Country-level and gridded estimates of wastewater production, collection, treatment and re-use*". We have chosen not to include the word 'modelled' in our dataset, as we do not want to give off the impression that the results are exclusively modelled (as the study is primarily underpinned by reported data at the country-level).

2. There is no distinction made in the dataset between industrial and domestic wastewater - which have very different characteristics and effects on environmental waters. It would thus be great to briefly discuss whether and how the combination of domestic and industrial wastewater may cause problems in the dataset, and in particular in the downscaling process. For example, industrial wastewater can be produced at locations with little correlation to population centers, i.e. at very distinct or remote locations compared to domestic wastewater - is this accounted for in the modeled return flows of PCR-GLOBWB? Also, I assume that the validation data cannot clearly distinguish between domestic and industrial wastewater as well? Related to this: Line 58 states for the first time that throughout the manuscript, domestic and industrial wastewater are not considered separately but lumped. As this is very important, it could be emphasized more, e.g. by referring more clearly to "combined domestic and industrial sources". This could also be done at other locations, where appropriate.

PCR-GLOBWB calculates water use (i.e. withdrawals, consumption and hence return flows) from the domestic and industrial sectors individually, which we have then lumped together for the downscaling procedure. Since the initial manuscript submission, we have further updated the return flows used for the downscaling procedure using a more recent water use dataset, developed at 5arc-min, from Water Futures and Solutions (WFaS) initiative (Wada et al., 2016). The use of this more recent dataset also facilitated an improved downscaling methodology and results.

In both the WFaS and PCR-GLOBWB methodologies, domestic demands are calculated on the basis of population and a country-specific per capita water use. Conversely, industrial demands are calculated on the basis of four socio-economic variables (GDP, electricity production, energy consumption and household consumption) (see Wada et al., 2011; Wada et al., 2014 and Wada et al., 2016 for details). Thus, industrial demand (and hence return flows) are simulated in areas taking into account multiple variables aside from just population. Regarding the question of the reviewer, the industrial return flows used do indeed account for industrial flows also being located in areas outside population centers.

We agree that the composition of industrial and domestic wastewater is different and that both have different environmental effects. We also strongly agree that a distinction between industrial and domestic wastewater is important for different applications. However, we choose to lump these flows for now. Domestic and industrial return flows are typically collected in the same (municipal) sewers before conveyance to wastewater treatment. As the reviewer points out, a distinction between domestic and industrial wastewater treatment can not be validated individually for this reason. We therefore prefer to present aggregated results of municipal wastewater, including both domestic and industrial wastewater.

The manuscript has been updated as appropriate to reflect these changes in using this more recent WFaS water use dataset (Wada et al, 2016).

Lines 207- 210: *"Return flows used for downscaling are calculated as gross - net water demands from the Water Futures and Solutions (WFaS) initiative for the years 2000 – 2010 (Wada et al., 2016). The WFaS water demand dataset follows the approach developed for PCR-GLOBWB (Wada et al., 2014)."*

Lines 217 – 226: *"Wastewater collection is assigned sequentially to grid cells with the largest downscaled produced wastewater flows. Thus, collected wastewater is preferentially allocated to grid cells with the highest levels of municipal activities, where central wastewater collection (and treatment) is assumed to be most economically feasible. Wastewater treatment is assigned to grid cells only where wastewater collection exists, at an average treatment rate calculated at the country-level. The treatment rate is calculated as the proportion of collected wastewater that undergoes treatment, and hence can differ from the country-level wastewater treatment percentage (which is calculated as the proportion of produced wastewater that is treated). For the downscaling of wastewater re-use an additional criterion was introduced to represent water scarcity, a key driver of wastewater re-use. The ratio of water demand to water availability was calculated. Grid cells within a country with a treated wastewater allocation are then ordered based off this ratio and treated wastewater re-use was assigned sequentially to these grid cells."*

3. Lines 62 and following: You state that "wastewater treatment improves the quality of 'used' water resources" and this notion seems to prevail throughout the introduction and discussion. But while "wastewater treatment" as a process certainly has the GOAL to improve water quality, what about the fact that substances that are not or cannot be treated by treatment facilities can cause the opposite effect: in these cases, wastewater treatment plants can represent point sources of pollution, especially in the case of emerging contaminants. This has not been addressed in the paper and I thus encourage the authors to at least briefly reflect on the issue.

This is an excellent point and we entirely agree that this should be considered in the manuscript. We recognise that wastewater collection and treatment processes, if insufficient, can concentrate particular pollutants (especially for emerging pollutants) and thus represent a point source for environmental contamination. We have added some sentences in the discussion section to reflect this:

Lines 494 – 503: *"It should be noted that while the aim of wastewater collection and treatment is to reduce pollutant loadings to minimise risks to human health and the environment, these facilities can also act as point sources of pollution. Wastewater collection concentrates pollutants which, can pose serious water quality issues if discharged with insufficient treatment. Furthermore, a range of emerging pollutants (e.g. pharmaceuticals, pesticides and industrial chemicals) are concentrated in wastewater collection networks (Geissen et al., 2015). These pollutants are of particular concern as they are not typically monitored for or sufficiently removed in wastewater treatment processes, with ambiguous risks posed to human and environmental health even in low concentrations (Deblonde et al., 2011; Geissen et al., 2015). The solution is not however to collect less wastewater, but to increase* *treatment in terms of percentage of collected wastewater, treatment level and the number of pollutants (UNEP, 2016).”*

4. Table 1 (Standardisation to 2015): There is very little explanation in the text about the rationale behind the standardization methods. It seems the main assumption is a linear behavior of wastewater amounts based on GDP, right? This could briefly be mentioned in the text. Also, for collection and treatment: I do not understand why the values are divided by GDP per capita but then not multiplied by GDP per capita but by total GDP. Is this just a typo?

For the standardisation to 2015, we indeed assumed a linear behavior with on GDP (for wastewater production) and GDP per capita (for wastewater collection and treatment). We have added a line to clarify and justify this choice in the text:

Lines 140 – 144: “*Wastewater production is assumed to be dependent upon both population size and per capita production (related to per capita wealth). Hence, we standardise wastewater production linearly with GDP, a combined metric of population size and wealth. Conversely, wastewater collection and treatment are assumed to be more dependent on economics, hence we linearly apply GDP per capita for standardisation*”.

We also would like to thank the reviewer for bringing the issue with GDP vs. GDP per capita to our attention. This is indeed an unfortunate typo. We have made the corrections to Table 1 (at line 155) and confirm that GDP per capita is indeed the correct variable that was used for standarising collection and treatment.

5. Figure 3: Very interesting figure. The one country that stands out to me as a surprise in wastewater production is Egypt. The Nile and Nile delta show also exceptionally high values in Figures 4 and 6. There is no comment about Egypt in the manuscript. Any explanations on why Egypt has so high domestic and industrial wastewater amounts?

We agree that Egypt is a particularly interesting country, and stands out in Figures 4 and 6 (which are updated, with the WFaS 5-arcmin water use dataset, but shows the same pattern.

It is worth noting that wastewater data for Egypt was cross referenced from three sources: 1) GWI 2015: 13,623 million m^3 yr^{-1}; 2) UNSD 2015: 11,899 million m^3 yr^{-1}; and 3) Aquastat 2012: 6,497 million m^3 yr^{-1} which, standarised to 2015, was 8,429 million m^3 yr^{-1}. Whilst some variation exists between these numbers, data from all three sources indicate a relatively high per capita wastewater production (between 91 – 147 m^3 yr^{-1} per capita). The final value determined (mean average from the three sources for 2015 data) for Egypt as 11,317 million m^3 yr^{-1} (122 m^3 yr^{-1} per capita) – which is relatively high (compared, for instance, to regional averages). This is further validated by estimates of Egypt’s domestic water use (200 l per capita per day in 2007), almost double that of Germanys (data from National Water Research Centre (Egypt).

In terms of the downscaled maps (Figures 4 and 6), population density is an important variable for quantification of domestic and industrial return flows in PCR-GLOBWB. Egypt’s population is of course heavily concentrated along the banks of the Nile and in the Nile Delta. This heavily concentrates the downscaled wastewater into relatively few gridcells (relative to the size of Egypt). Next to this, we expect that the domestic + industrial return flows (or wastewater) values may also be high due to the relatively low water use efficiencies and system losses.

6. To my knowledge, the European dataset of wastewater treatment plants reports treatment capacity only in Population Equivalent (PE); however, the manuscript states that the volume flow rate was obtained based on a linear regression for plants reporting both parameters (PE and volume). It would be interesting to know how many plants included this information since the openly available dataset at the EEA website seems not to provide the volume flow rate.

The reviewer makes a good point here with regards to our need to convert wastewater treatment in population equivalent to volume flow rate for validation purposes. We indeed used a linear relation between Population Equivalent (PE) and volume flow rate for wastewater treatment plants that reported both of these variables, and applied this to plants where only the PE was reported.

Fortunately, we were able to obtain a decent number of data points both for the global database (GWI) and specifically for Europe (EEA) in order to do the linear regression.

For the EEA dataset, both PE and volume flow rate (in m^3 yr^{-1}) data were available for 8,309 treatment plants. The linear relationship was applied to 17,593 plants with only treatment capacity in PE, to estimate treatment capacity in volume flow rate units. Predicted vs. reported wastewater treatment capacity is displayed for the EEA plants where both PE and volume flow rate units (e.g. m^3 yr^{-1}) are reported in Figure R1 ($R^2 = 0.80$).

For the GWI dataset, this was available for 227 wastewater treatment plants, with the linear relation applied to 83 plants with capacity only reported in PE. The remaining plants has their capacities only reported in volume flow units. It is important to note that wastewater treatment plants located in the US and Europe were excluded from the GWI dataset to avoid plants potentially being counted multiple times if contained in the GWI dataset + the EEA or US EPA dataset. Predicted vs. reported wastewater treatment capacity is displayed for the GWI plants where both PE and volume flow rate units (e.g. m^3 yr^{-1}) are reported in Figure R2 ($R^2 = 0.81$).

All wastewater data from the US EPA were reported in volume flow rate units (million gallons per day) which was converted into m^3 yr^{-1}.

With regards to the EEA data, we found this data to be freely available. If the reviewer is interested in this dataset, they can download this information from Waterbase (https://www.eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-6) and consult the worksheet named "UWWTPS". Providing this dataset has not since been adjusted, information for plant latitude (column AF); longitude (column AH); load entering UWWTP in PE (column AG) and wastewater treated (column BP) in m^3 yr^{-1} can be obtained. Alternatively, the reviewer is welcome to contact us directly if they would like the plant level data for the EU. As part of this paper, we have already collated important information for them various spreadsheets provided by the EEA into a single spreadsheet and undertaking some basic formatting.

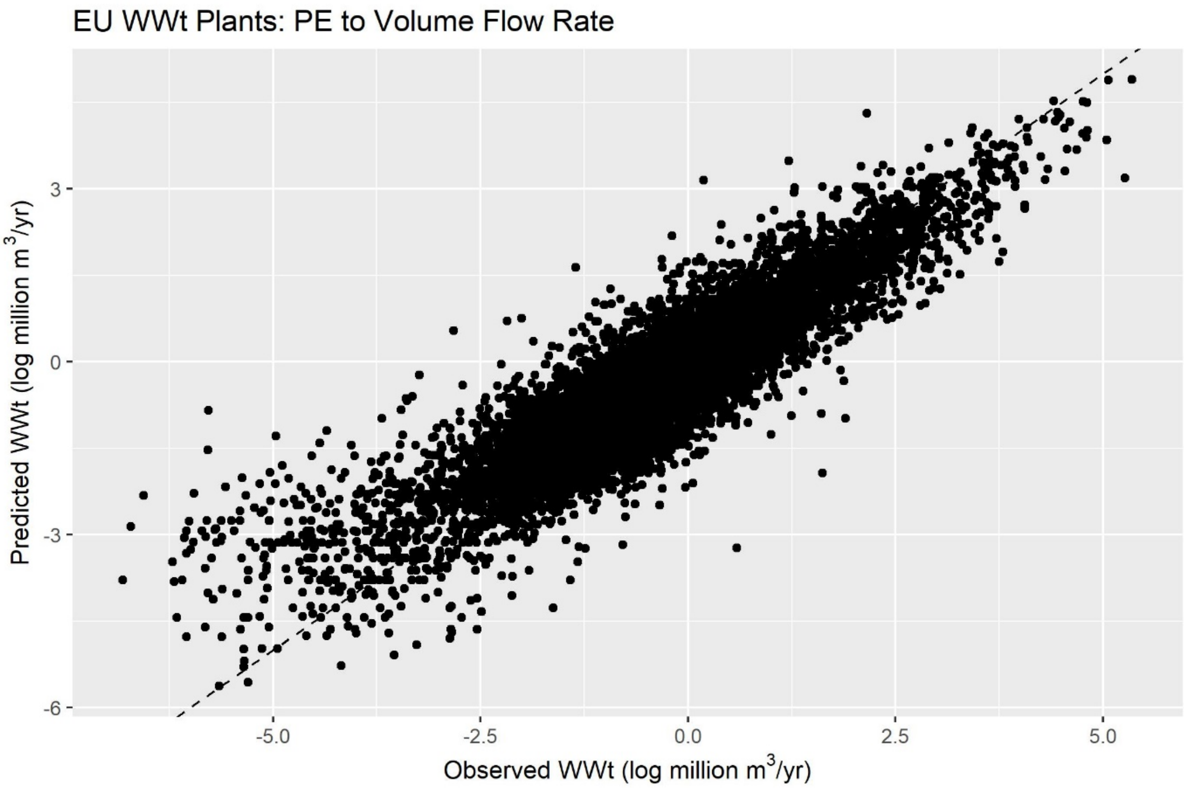

Figure R1. Predicted vs. reported wastewater treatment for EU wastewater treatment plants reporting treatment capacity in both population Equivalent (PE) and in volume flow rate units (e.g. million m^3 yr^{-1}).

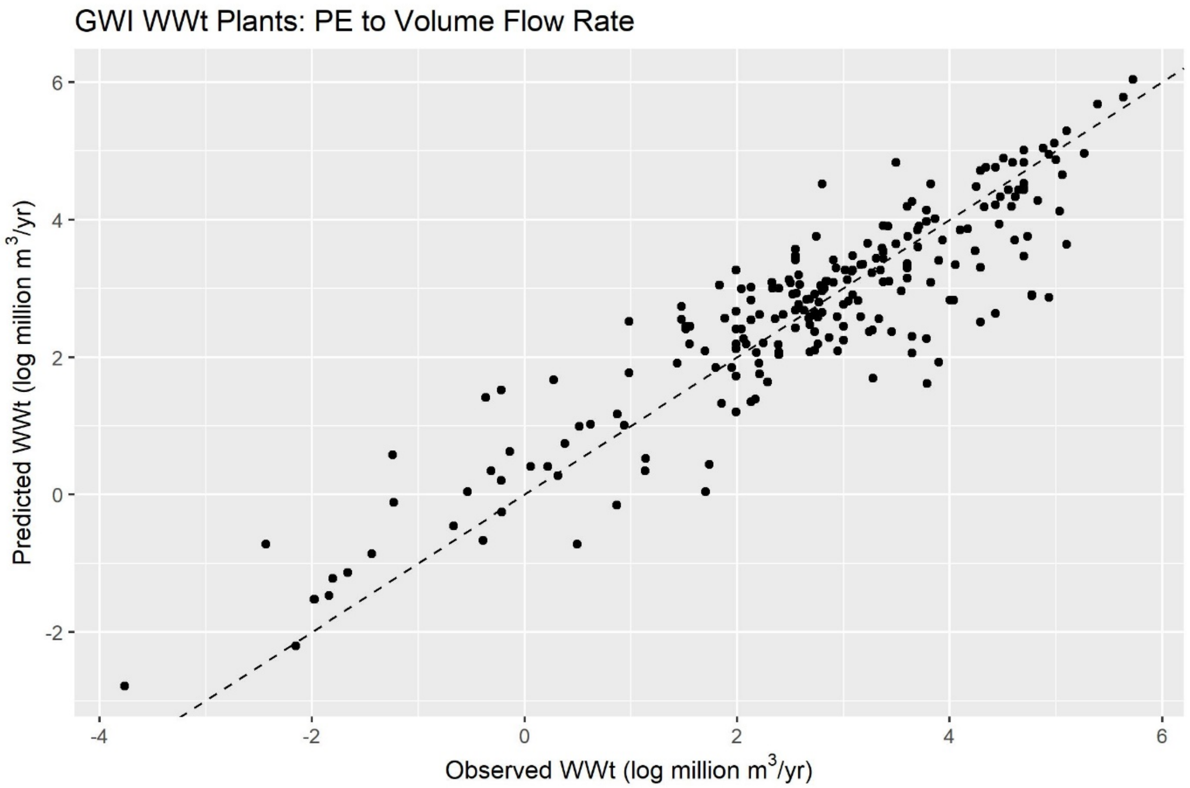

Figure R2. Predicted vs. reported wastewater treatment for GWI wastewater treatment plants reporting treatment capacity in both population Equivalent (PE) and in volume flow rate units (e.g. million m^3 yr^{-1}).

7. Line 437 and following: You say: "This may occur due to discrepancies between the design (i.e. maximum) capacity of wastewater treatment plants . . ." Ok, that is a fair point. But the other option is that your model overpredicts in places without treatment plants and therefore underpredicts in places with treatment plants. This potential model bias should be acknowledged and briefly discussed.

We agree that this potential bias might also explain these discrepancies. We think this is ultimately depends on the downscaling method for wastewater production (i.e. using modelled return flow data from PCR-GLOBWB), on which quantifications of wastewater treatment are based. We have tried to explain this in more detail in the text:

Lines 437 – 441: *"Furthermore, uncertainties in the data used as basis for downscaling of wastewater production (i.e. PCR-GLOBWB return flows) directly impacts the downscaled results of wastewater treatment. For example, the underprediction of return flows in urban areas and overprediction in rural areas could lead to the overprediction of wastewater treatment in areas without treatment plants and underprediction of wastewater treatment for grid cells with large treatment capacities."*

8. Line 244-245: "For validating downscaled wastewater re-use, only plants (with treatment capacity > 1 million m3 yr-1) using tertiary or higher wastewater treatment technologies were considered." The rationale for this decision is not clear to me.

Unfortunately, plant-level data on wastewater re-use is limited. Due to the lack of data, assumptions had to be made for validating wastewater re-use. Aside for the limited number of plants specifically designated as re-use facilities from GWI (78 wastewater re-use plants), we assumed that tertiary or higher wastewater treatment processes likely are most strongly related to wastewater re-use (as these treatment levels are a pre-requisite for safe re-use for most applications). We narrowed the scope to larger wastewater treatment plants only (>1 million m^3 yr^{-1}), where tertiary+ treated wastewater is potentially available for re-use in substantial volumes and to exclude highly localised wastewater treatment facilities (e.g. for specific industrial facilities) which are very difficult to capture in lieu of poor data availability.

9. Figure 1 shows that there are data for only ~half of global countries available (e.g. production data are available for 118 countries), yet 90% of population is covered by data. The only explanation for this is that all the high-population countries are included in those countries for which data exist, correct? It may be worth pointing this out as initially I was confused on how these numbers match up. I found some explanations later in the manuscript, but maybe this general fact could be stated earlier.

The reviewer is correct. Reported data was typically more available for large countries as opposed to smaller ones. We have tried to make this more clear in the text when the comparison between % population and number of countries with reported data is first mentioned.

Lines 147 – 148: *"Reported wastewater data was available for the majority of the world's most populous countries. This results in a the high percentage population coverage relative to the number of countries."*

Minor Comments

Throughout the text, the authors use the expression "data" in singular form ("data is . . ."). I am more used to data in plural form ("data are . . .").

We agree with the reviewer. This has been corrected throughout the manuscript.

Also throughout the text, the authors use the expression "whilst" (many times). Its my understanding that "whilst" may be perceived as 'archaic' in American English (https://en.wikipedia.org/wiki/While). So maybe use "while" instead?

We have changed all occurrences of "whilst" to "while", the more familiar formulation of the word in American English.

Line 24 (and possibly elsewhere): The expression "significant" is often reserved for instances where it refers to statistical methods. Here, an alternative might be to use "substantial".

We thank the reviewer for this comment, and agree that "substantial" is a better word choice for instances not referring to statistical methods. This has been adjusted throughout the manuscript.

Line 25: replace "containing" with "comprising"?

This has been changed.

Line 28: I suggest spelling out the first occurrence of SDG here (or remove the example)

We have removed the example of the SDGs in the abstract for readability. The anacronym SDG is now spelt out in the first occurrence in the manuscript instead.

Line 80: "that ensure" instead of "to ensure"?

This has been changed.

Line 88: rephrase “whereby . . .” - maybe “which includes a target that . . .”

This line has been reformulated in line with the recommendation to rephrase.

Line 89: add a space in “SDG 6.3”

This has been changed.

Line 98: say “to a grid level of 5 arc-minute spatial resolution”

This has been changed.

Figure 1: I cannot find the letters (a), (b) and (c) reflected in the figure, so it is difficult to find out which panels the caption refers to. Also, I suggest removing the asterisk from the figure and simply add the definition of ‘population coverage’ as part of the normal caption.

Thanks for noticing that (a), (b) and (c) was missing from the figure. This was a mistake and has now been corrected. The asterisk has been removed as recommended, and the figure caption has been updated. Figure panels b and c have also been increased slightly in size for better readability.

Line 117: add “(Table 1)” after “. . . databases”

This has been added.

Lines 125-126 (and elsewhere): I find the use the acronyms, the article “the”, as well as the verbs not consistent here. I would say “GWI reports . . . whereas FAO reports . . . and UNSD reports” etc.

This has been changed in the suggested way.

Line 126: say “. . . reported by UNSD”

This should read more clearly now with the changes to lines 125-126.

Lines 139-140: repetitive use of “both” - delete one?

This has been changed.

Table 1: start title with “Wastewater data sources and population coverage by region and economic aspects. . .” Also, the footnotes of the table could be shortened. E.g. the square brackets always refer to the number of countries, so this could be explained once in the title and does not need to be repeated for each of the footnotes.

Thanks for this suggestion to alter the title and footnotes. These have been changed.

Line 166 (and possibly elsewhere): there are some instances where “per capita” is written as “per Capita” (capitalized)

“per capita” (lowercase) is now consistently used throughout the manuscript.

Line 168-169: “Data was transformed, as appropriate, to ensure normality.” This statement is not clear to me. Does it refer to what is called “sqrt” in Table 3, which I guess means that the square-root of values was calculated? Could both instances be clarified, e.g. by adding a little more information in this sentence here?

Some variables (e.g. GDP, population) were log-transformed to limit skew in the independent variables (which can vary across many orders of magnitude) and to achieve normality. Alternatively, square-root (sqrt) transformation is used for desalination capacity per capita as this data-set contained zero values (countries with no desalination) and thus is inappropriate for log transformation. We have further clarified this in the text:

Lines 175 – 176: *"Data was transformed, either using a log or square root transformation, to reduce the skew in the independent variables and to ensure normality."*

Table 2: spelling of "Agricultural Land" should be "Agricultural land"

Thanks for noticing this – the appropriate change has been made.

Line 201: The eight regions are listed here for the first time, but no explanation is provided on what exactly defines these regions. Is this some official breakdown so that one could look up the countries that belong to each region?

Thanks for this. The regional classifications are taken from the World Bank, the same as for the countries and income classifications. We agree this should be more clear in the text, so we have added this.

Line 215: "occur" instead of "occurs"

This has been changed.

Line 241: repetition of "both"

One occurrence of the word "both" has been removed.

Line 243: "where aggregated PER CELL"?

Correct. This has been added.

Line 248: "were" instead of "was"

This has been changed.

Line 254 and 257: While most explanations in this paragraph are in the past tense, two verbs are in present tense ("is expanded" and "is then compared"). Typo?

Thanks for noticing this. This has been changed.

Line 261: "were" instead of "was"

This has been changed.

Line 289: "Human Development Index" (as it was also capitalized elsewhere)

This has been changed.

Line 290-291: say "was found to have the strongest influence on"

Good suggestion. This has been changed.

Line 311: "nations" (plural)

This has been changed.

Figure 2: Could add the number of countries that are displayed in each panel, e.g. add "n = ...". Also, the graphs may be clearer if using white instead of grey background.

We have added the number of countries in each panel, as suggested. We prefer to keep the backgrounds of the graphs grey.

Line 326: move "billion" after parentheses

This has been changed.

Line 331: "being from" instead of "from"

This has been changed.

Line 353: "World Health Organization's" (with apostrophe)

This has been changed.

Line 362: "indicate" instead of "indicates"

This has been changed.

Line 379: add commas before and after "respectively"

This has been changed.

Line 391: delete "regions"

This has been changed.

Line 397: "treat" instead of "treated"

This has been changed.

Line 398: "than in" instead of "than by"

This has been changed.

Table 4, title: Start with "Wastewater production, collection, treatment and re-use (billion m3 yr-1) by region and economic development level." I suggest changing "brackets" to "parentheses" (as brackets in American English would refer to squared brackets). And say "regressions" (plural).

Thanks for this suggestion. We have made altered the title as recommended.

Line 421: "yr-1" instead of "/year". Also, "occur" instead of "occurs"

This has been changed.

Line 422: "collection . . . and treatment . . . are" (instead of "is")

This has been changed.

Line 426: "with only available wastewater resources" not clear, wrong wording?

We agree this is ambiguous wording. We have made the appropriate changes in the text to clarify this.

Line 456: I suggest using "underpinning source data" instead of "underlying source data"

This has been changed.

Line 472: "upon which country-level estimates incorporate" seems to be incorrect wording

We agree this is incorrectly worded. We have changed the wording in the manuscript.

Line 479: I suggest breaking this very long paragraph into 2 here

This has been changed.

Line 486: say "factors" instead of "drivers" to avoid repetition

This has been changed.

Line 489: say "of untreated" (add "of")

This has been changed.

Line 496: “Whilst our results also rely on this approach, we instead used. . .” This sounds odd (first you say you do the same, then you say ‘instead’) - rephrase?

We agreed that this is an ‘odd’ statement. We have adjusted the wording to make this more clear.

Line 512: The expression “acreage” may not be known to all readers. Could just say “spatial extent”

We prefer to keep the term “acreage” here, as this is the terminology used in the referenced work.

Line 519: close the parentheses

This has been changed.

Line 522: “for as a baseline for”? should this be “as a baseline for”?

This has been changed.

Line 525: “. . . problems of discrepancies in data reporting years and missing data are overcome.” It sounds quite optimistic that the problems are truly “overcome” (i.e. solved). Maybe say “reduced” instead?

Good suggestion. We now use the word “reduced” instead.

Lines 528-529: repetitive use of “particularly”

This has been changed.

Lines 549-551: you use the word “such” three times here

This has been changed.

Lines 550-551: The grammar/verb of the description of point (4) seems incorrect. Change “creating” to “create”?

This has been changed.

References: Reviewer 1

Deblonde, T., Cossu-Leguille, C., and Hartemann, P.: Emerging pollutants in wastewater: a review of the literature, International journal of hygiene and environmental health, 214, 442-448, 10.1016/j.ijheh.2011.08.002, 2011.

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Wada, Y., Beek, L. P. H., Viviroli, D., Dürr, H., Weingartner, R., and Bierkens, M. F. P.: Global monthly water stress: II. Water demand and severity of water, Water Resources Research - WATER RESOUR RES, 47, 10.1029/2010WR009792, 2011.

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Reviewer #2

General comments from reviewer

This study provided the comprehensive and consistent global outlook on the state of wastewater production collection treatment and reuse. And the country level wastewater data are downscaled and validated at 5 arc- minute resolution. Its results represent the first efforts to global wastewater collection treatment and reuse at the subnational level. It is a very interesting and useful work for the wastewater research. And the quality of the data set as submitted is high. The data analysis and discussions are sufficient. So I think it prepared well for publication. It analyzed the relationship among the production, collection, treatment and reuse of wastewater, the income level and the population.

We thank the reviewer for reading the manuscript and providing their feedback. We were very pleased to read that the reviewer thinks the dataset is of high quality and useful for wastewater research.

However, I think the influence from the pollution of agriculture, especially for the global grain production areas, cannot be ignored. So I suggest the author to add the analysis or discussion of this part. It may be more perfect.

We agree that agricultural runoff is a very important source of water pollution, and that we should reflect more upon this in the Discussion section of the manuscript. Whilst a more detailed analysis of diffuse and point source pollution from the agricultural sector would be beneficial for the water quality modelling community, this is outside the scope of this study, which solely focuses on municipal wastewater (i.e. domestic and industrial sources) for a number of reasons.

Firstly, country-level data is much more readily available for the municipal sector. This makes our (data-driven) approach more applicable for these sectors. Return flows from agricultural activities at the global scale are more typically quantified by modelling of irrigation water demand (net and gross) and withdrawal.

Secondly, agricultural runoff, which is an important source of pollution by the agricultural sector, is rarely collected or treated (e.g. WWAP, 2017) and hence far less applicable to this study. Conversely, collection (particularly sewers) and treatment infrastructure are very important for determining the fate of pollutants generated by municipal activities (e.g. collection and treatment infrastructure as point sources of pollutants, abatement of pollutant levels via treatment processes).

To address this comment, we have added the following lines to the discussion section of the manuscript:

Line 461 – 466: *"While agricultural runoff is also a substantial source of pollution, this is outside the scope of this study. Country-level data on agricultural runoff is sparse, necessitating modelling approaches to quantify irrigation return flow by calculating net demand (e.g. based on crop composition and irrigated area per grid cell), gross irrigation demand (to account for irrigation efficiency and losses) and water withdrawals (Sutanudjaja et al., 2018). Agricultural runoff is also rarely collected or treated (UNEP, 2016), hence is less applicable for inclusion in this study."*

References: Reviewer 2

Sutanudjaja, E., Beek, R., Wanders, N., Wada, Y., Bosmans, J., Drost, N., Ent, R., de Graaf, I., Hoch, J., de Jong, K., Karssenberg, D., López, P., Pessenteiner, S., Schmitz, O., Straatsma, M., Vannametee, E., Wisser, D., and Bierkens, M.: PCR-GLOBWB 2: A 5 arcmin global hydrological and water resources model, Geoscientific Model Development, 11, 2429-2453, 10.5194/gmd-11-2429-2018, 2018.

UNEP: A Snapshot of the World's Water Quality: Towards a global assessment, United Nations Environment Programme, Nairobi, Kenya, 162pp, 2016.

WWAP: The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource, Paris, UNESCO, 2017.

~~Spatially-explicit~~Country-level and gridded estimates of~~ global~~ wastewater production, collection, treatment and re-use~~.~~

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Abstract.

Continually improving and affordable wastewater management provides opportunities for both pollution reduction and clean water supply augmentation, while~~st~~ simultaneously promoting sustainable development and supporting the transition to a circular economy. This study aims to provide the first comprehensive and consistent global outlook on the state of domestic and industrial wastewater production, collection, treatment and re-use. We use a data-driven approach, collating, cross-examining and standardising country-level wastewater data from online data resources. Where unavailable, data are~~is~~ estimated using multiple linear regression. Country-level wastewater data are subsequently downscaled and validated at 5 arc-minute (~10 km) resolution. This study estimates global wastewater production at 359.4 billion m^3 yr^{-1}, of which 63% (225.6 billion m^3 yr^{-1}) is collected and 52% (188.1 billion m^3 yr^{-1}) is treated. By extension, we estimate that 48% of global wastewater production is released to the environment untreated, which is substantially~~significantly~~ lower than previous estimates of ~80%. An estimated 40.7 billion m^3 yr^{-1} of treated wastewater is intentionally re-used. Substantial differences in per capita wastewater production, collection and treatment are observed across different geographic regions and by level of economic development. For example, just over 16% of the global population in high income countries produce 41% of global wastewater. Treated wastewater re-use is particularly substantial~~significant~~ in the Middle East and North Africa (15%) and Western Europe (16%), while ~~containing~~ comprising just 5.8% and 5.7% of the global population, respectively. Our database serves as a reference for understanding the global wastewater status and for identifying hotspots where untreated wastewater is released to the environment, which are found particularly in South and Southeast Asia. Importantly, our results also serve as a baseline for evaluating progress towards many policy goals that are both directly and indirectly connected to wastewater management~~ (e.g. SDGs)~~. Our spatially-explicit results available at 5 arc-minute resolution are well suited for supporting more detailed hydrological analyses such as water quality modelling and large-scale water resource assessments, and can be accessed at: https://doi.pangaea.de/10.1594/PANGAEA.918731 (Jones et al., 2020).~~ A temporary link to this dataset for the review process can be accessed at: https://www.pangaea.de/tok/6631ef8746b59999071fa2e692fbc492c97352aa.~~

1. Introduction

Clean water is essential for supporting human livelihoods, achieving sustainable development and maintaining ecosystem health. All major human activities, such as crop and livestock production, manufacturing of goods, power generation and domestic activities rely upon the availability of water in both adequate quantities and of acceptable quality at the point of intended use (van Vliet et al., 2017;Ercin and Hoekstra, 2014). It is increasingly recognised that conventional water resources such as rainfall, snowmelt and runoff captured in lakes, rivers and aquifers are insufficient to meet human demands in water scarce areas (Jones et al., 2019;Hanasaki et al., 2013;Kummu et al., 2016). Whilest increases in water use efficiencies can somewhat reduce the water demand and supply gap, these approaches must be combined with supply and quality enhancement strategies (Gude, 2017). Conventional supply enhancement strategies, such as reservoir construction, surface water diversion and pipeline construction are contingent on geographic and climate factors, can face strong public opposition and often lack water quality considerations.

A growing set of viable but unconventional water resources offer enormous potential for narrowing the water demand-supply gap towards a water-secure future. Unconventional water resources encapsulate a range of strategies across different scales, from localised fog-water and rainwater harvesting, to mega-scale desalination plants and wastewater treatment and re-use facilities (Jones et al., 2019;Morote et al., 2019;Qadir et al., 2020). The use of unconventional water resources has grown rapidly in the last few decades, often out of necessity, and their importance across various geographic scales is already irrefutable (Jones et al., 2019;Qadir et al., 2018). Furthermore, continually improving unconventional water resources technologies have permitted more efficient and economical 'tapping' of water resources which were previously unusable due to access constraints or the added costs related to unsuitable water quality (e.g. seawater desalination, wastewater treatment).

Wastewater is broadly defined as 'used' water that has been contaminated as a result of human activities (Mateo-Sagasta et al., 2015). Whilest agricultural runoff is rarely collected or treated (WWAP, 2017), return flows from domestic and industrial sources (henceforth 'wastewater') can be collected in infrastructure including piped systems (sewerage) or on-site sanitation systems (septic tanks; pit latrines). Wastewater is increasingly recognised as a reliable and cost-effective source of freshwater, particularly for agricultural applications (WWAP, 2017;Jiménez and Asano, 2008). Yet, wastewater remains an 'untapped' and 'undervalued' resource (WWAP, 2017). Wastewater treatment aims to improves the quality of 'used' water sources to reduce contaminant levels below sectoral quality thresholds for intentional re-use or to minimise the environmental impacts of wastewater return flows. Treated wastewater flows can also provide a substantialsignificant source of (clean) freshwater flows for maintenance of river flows, especially during drought (Luthy et al., 2015). Where treated wastewater discharges form a substantial part of the river flow, de-facto wastewater re-use, defined as the incidental presence of treated wastewater in a water supply, can be high (Rice et al., 2013;Beard et al., 2019). Treated wastewater can also be used for groundwater recharge, helping to preserve the viability of freshwater extraction from groundwater into the future (Qadir et al., 2015), in addition to applications in agroforestry systems (El Moussaoui et al., 2019) and aquaculture (Khalil and Hussein, 2008). In summary, wastewater treatment can improve river water quality and ecosystem health, while~~st~~ providing an alternative source of freshwater for human use and subsequently reducing competition for conventional water supplies.

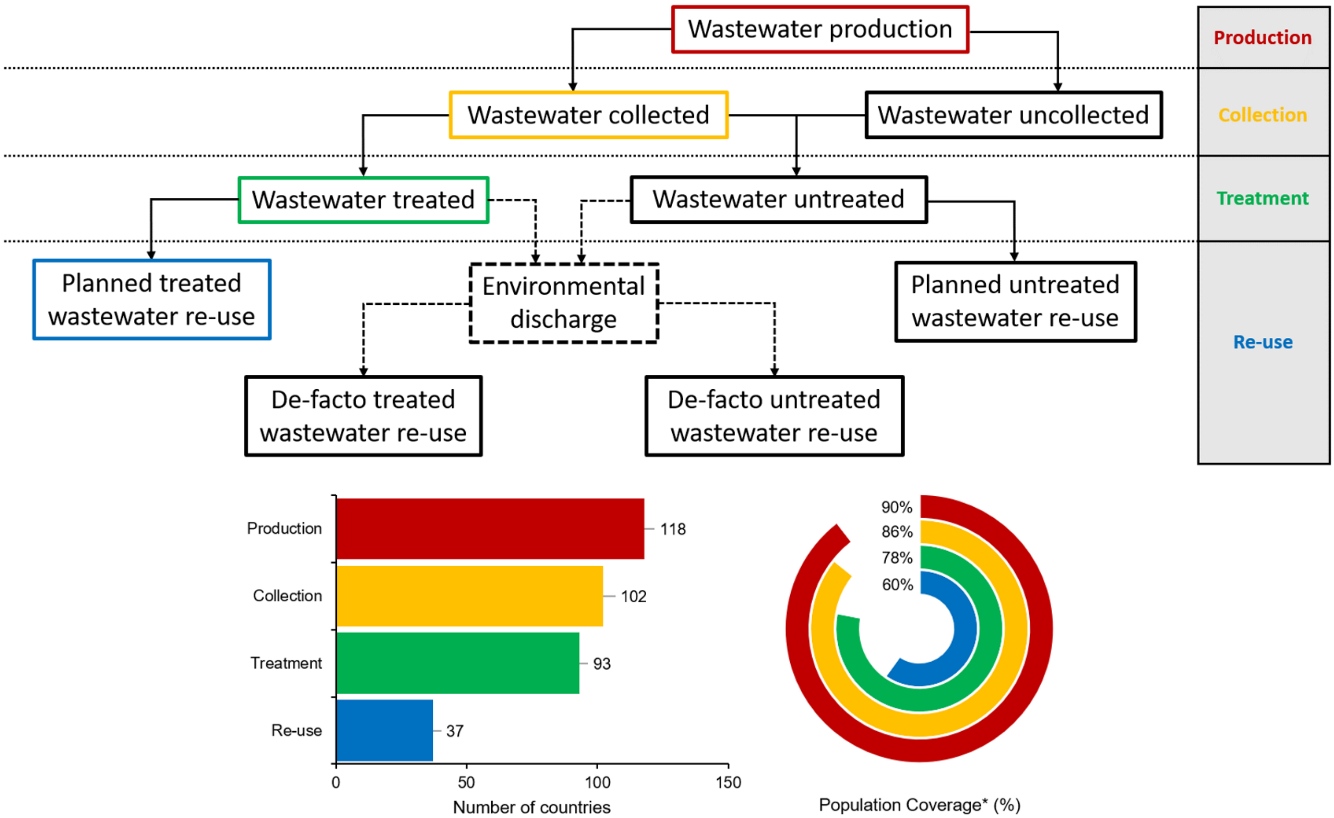
Historically, wastewater (both treated and untreated) has been predominantly used for non-potable purposes, particularly agriculture and landscape irrigation (Qadir et al., 2007;WWAP, 2017;Zhang and Shen, 2017). Agricultural activities are expected to increasingly rely on alternative water resources, as this sector has the largest water demands globally (Wada et al., 2013). Furthermore, the agricultural sector faces reductions in conventional water resources allocation (Sato et al., 2013). The reliable supply of water, reduced need for additional fertilizer and potential for growing high value vegetables promote wastewater irrigation in water-scarce developing countries (Sato et al., 2013). However, much of the wastewater currently re-used is inadequately treated or even untreated (Qadir et al., 2010;Scott et al., 2010). Demands for wastewater are increasing at a faster pace than treatment solutions and institutions that~~o~~ ensure the safe distribution and management of wastewater (Sato et al., 2013). The primary challenge in promoting re-use is ensuring safety – both for human and ecosystem health – and thus ensuring that wastewater is adequately treated prior to use or environmental discharge (WWAP, 2017). This is needed to achieve the required paradigm shift in water resources management, whereby wastewater is viewed as a resource (for energy, nutrients and water) rather than as 'waste' (WWAP, 2017;Qadir et al., 2020).

To understand the current state and explore the future potential of wastewater as a resource, a comprehensive and consistent global assessment of wastewater production, collection, treatment and re-use is required. This information is essential for assessing progress towards Sustainable Development Goal (SDG) 6, ~~whereby one of the~~such as SDG 6.3 ~~targets is~~that specifically focuses~~d~~ on achieving water quality improvements through~~ by~~ halving the proportion of untreated wastewater and promoting safe re-use globally~~ (SDG6.3)~~. Furthermore, this information is important for identifying hotspots where improvements in wastewater management are highly necessary and as input data for a range of scientific assessments (e.g. stream water quality dynamics, water scarcity assessments). However, the availability of wastewater data at the continental and global scales is sparse, and often outdated or from inconsistent reporting years (Sato et al., 2013). Previous studies remain limited in their approach and estimates, relying on a few data sources covering less than half of the countries across the world (Mateo-Sagasta et al., 2015;Sato et al., 2013). A recent study explored the global and regional 'potential' of wastewater as a water, nutrient and energy source, but did not address the collection, treatment and re-use aspects of wastewater (Qadir et al., 2020). This paper presents the first global assessment of spatially-explicit wastewater production, collection, treatment and re-use, consistently combing different data sources. Country-level quantifications are downscaled to a grid~~ded~~ level of ~~(~~5 arc-minute ~~resolution) level~~ for inclusion in large-scale water resource assessments and water quality models.

2. Methods

2.1 Wastewater Data Sources

The fate of domestic and industrial wastewater after production can follow a number of paths (Figure 1). Wastewater from these activities can be collected, typically in sewers, septic tanks or pit latrines, or uncollected and discharged directly to the environment (e.g. open defecation). Collected wastewater can undergo treatment, ranging from basic primary treatment (removing suspended solids) to specialised tertiary or triple barrier treatment (nutrient removal, toxic compound removal), or can be discharged to the environment untreated (Mateo-Sagasta et al., 2015). When treated, wastewater can be released to the environment or intentionally re-used as a 'fit-for-purpose' water source. Untreated wastewater can similarly be discharged to the environment or intentionally used as a source of freshwater. Furthermore, both treated and untreated wastewater can be used unintentionally where wastewater is incidentally present in a water supply ('de-facto reuse').


Wastewater production
Production
Wastewater collected
Wastewater uncollected
Collection
Wastewater treated
Wastewater untreated
Treatment
Planned treated wastewater re-use
Environmental discharge
Planned untreated wastewater re-use
Re-use
De-facto treated wastewater re-use
De-facto untreated wastewater re-use
Production
Collection
Treatment
Re-use
118
102
93
37
0
50
100
150
Number of countries
90%
86%
78%
60%
Population Coverage* (%)

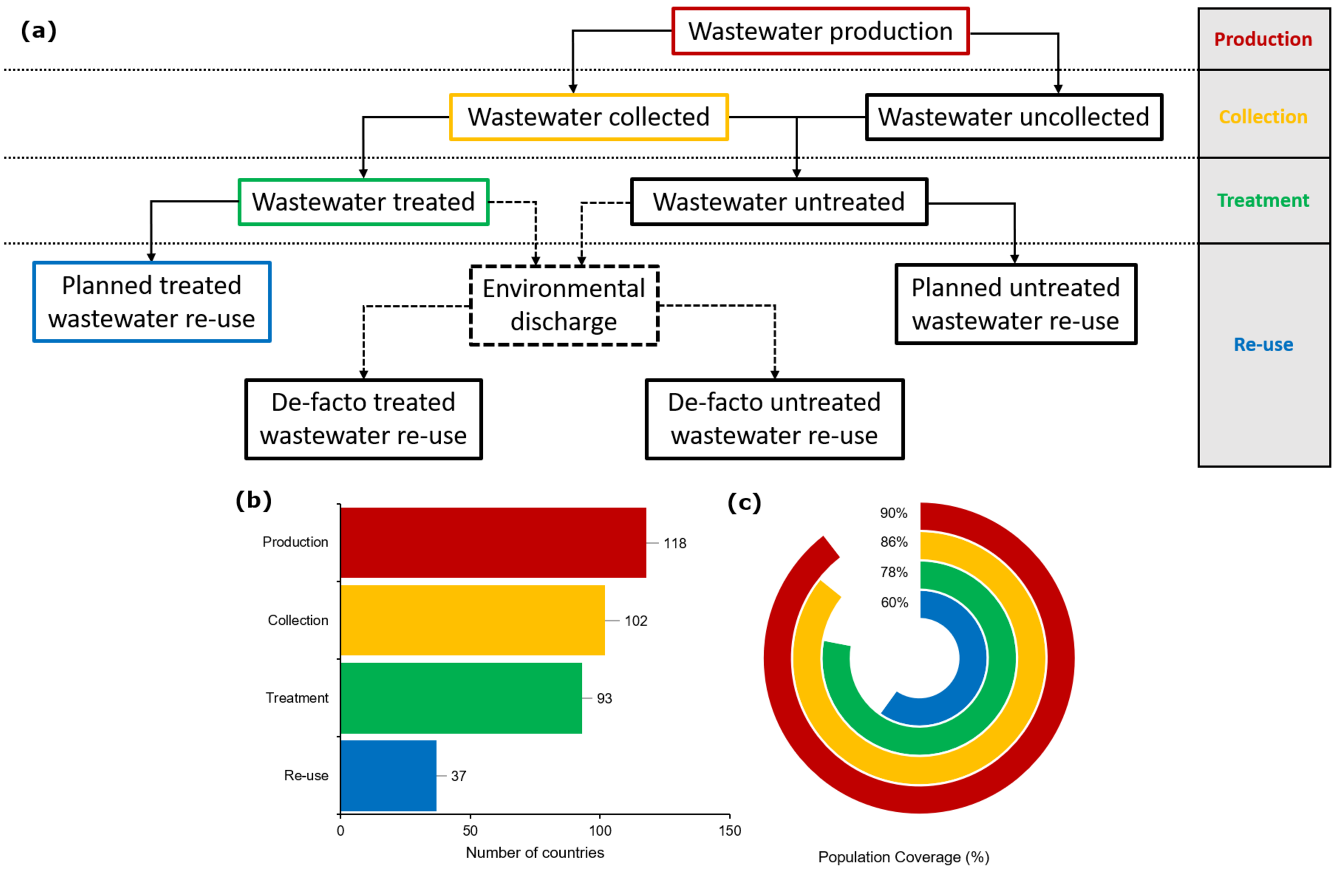


Fig 1. Fate of wastewater (a), including wastewater data availability with number of countries for which wastewater data is available (b) and percentage of population coverage (i.e. the proportion of the global population for which wastewater data is available) (c).

~~*Population coverage indicates the proportion of the global population for which wastewater data is available.~~

Country-level wastewater data was collated from four online databases (Table 1): Global Water Intelligence (GWI, 2015); Food and Agricultural Organisation of the United Nations (FAO-AQUASTAT, 2020), Eurostat (Eurostat, 2020) and ~~the~~ United Nations Statistics Division (UNSD, 2020). For consistency, the year 2015 was selected for all wastewater data. Where wastewater data from the online sources was reported in a different year (up to a maximum of 10 years, i.e. 2006 onwards), all wastewater data was standardised to 2015 based on data from the most recent reporting year (see Table 1 for the standardisation method).

Data from different sources was cross examined to check for consistency and to remove implausible data. Where large discrepancies (>one order of magnitude) existed between different data sources for a country, data points were excluded. For example, GWI report Kazakhstan to produce 6,205 million $m^3 yr^{-1}$, whereas ~~the~~ FAO report just 411 million $m^3 yr^{-1}$. Similarly, ~~the~~ FAO report Moldova to produce 46.7 million $m^3 yr^{-1}$ compared to 672.1 million $m^3 yr^{-1}$ by ~~the~~ UNSD. In total, reported data for 11 countries were excluded for wastewater production. For wastewater collection and treatment, percentage data was cross referenced with reported connection rates (i.e. percentage population connected to wastewater collection/ treatment). Six and seven countries were excluded for collection and treatment, respectively. For example, GWI report a 95.2% collection rate for Azerbaijan, whil~~est the~~ UNSD report that only 32.4% of people are connected to wastewater collection systems. Similarly, GWI report ~~only~~ a 17% treatment rate in Hong Kong, whereas ~~the~~ UNSD report that 93.5% of people are connected to wastewater treatment plants. No data points were excluded for wastewater re-use. In a small number of cases where percentage values obtained were marginally illogical (i.e. wastewater collection < wastewater treatment; wastewater treatment < wastewater re-use), percentage values were set to the proceeding level in the wastewater chain (Figure 1).

Table 1 displays the data sources and the associated number of countries with wastewater data for production, collection, treatment and re-use. The procedure for standardising ~~the~~ data to the year 2015, when required, is presented. Wastewater production is assumed to be dependent upon both population size and per capita production (related to per capita wealth). Hence, we standardise wastewater production linearly with GDP, a combined metric of population size and wealth. Conversely, wastewater collection and treatment are assumed to be more dependent on economics, hence we linearly apply GDP per capita for standardisation. The methods used to compile wastewater production, collection, treatment and re-use data from multiple sources to provide a single quantification per country is also displayed. Lastly, the population coverage in ~~both~~ percentage terms and by the number of unique countries is displayed both per geographic region and by economic classification. The number of unique countries and the population coverage of data at each stage of the wastewater chain is also displayed in Figure 1. Reported wastewater data was available for the majority of the world's most populous countries. This results in a high percentage population coverage relative to the number of countries. Both the number of countries and population coverage reduces through the wastewater chain, with available wastewater data decreasing from 118 to 37 countries (90% to 60% population coverage) from wastewater production to wastewater re-use data.

Table 1. Wastewater data sources and ~~availability by~~ population coverage by regional and economic aspects, including~~and~~ the number of unique countries (in square brackets). Method for standardisation of wastewater data to 2015 and the method for compiling wastewater data from multiple sources into a single quantification per country.

	Data sources*	Standardisation to 2015	Data compiling method	Regional aspects	Economic aspects

				Region	Population coverage **	Classification	Population coverage***
Production	GWI [94] FAO [98] UNSD [23] Eurostat [20]	Divide by GDP ($) in reporting year, multiply with GDP ($) in 2015.	Average of all available sources.	North America	100% [2]	High	99.4% [48]
				Latin America & Caribbean	93.9%) [19]		
				Western Europe	99.8% [19]	Upper middle	98.0% [34]
				Middle East & North Africa	98.8% [19]		
				Sub-Saharan Africa	49.6% [17]	Lower middle	94.6% [31]
				Southern Asia	96.4% [4]		
				Eastern Europe & Central Asia	89.4% [23]	Low	13.3% [5]
				East Asia & Pacific	95.3% [15]		
Collection	GWI [95] FAO [55]	Divide by GDP per ~~C~~capita ($/capita) in reporting year, multiple with GDP per capita ($/capita) in 2015.	GWI data prioritised. FAO data if unavailable.	North America	100% [2]	High	99.4% [47]
				Latin America & Caribbean	96.7% [20]		
				Western Europe	99.8% [18]	Upper middle	97.7% [29]
				Middle East & North Africa	88.3% [17]		
				Sub-Saharan Africa	61.1% [13]	Lower middle	81.0% [21]
				Southern Asia	96.4% [4]		
				Eastern Europe & Central Asia	69.9% [16]	Low	34.9% [5]
				East Asia & Pacific	83.6% [12]		
Treatment	GWI [76] FAO [78] UNSD [21]	Divide by GDP per ~~C~~capita ($/capita) in reporting year, multiple with GDP per capita ($/capita) in 2015.	GWI data prioritised. FAO or UNSD where unavailable (most recent reporting year prioritised)	North America	100% [2]	High	98.4% [46]
				Latin America & Caribbean	90.0% [17]		
				Western Europe	99.8% [19]	Upper middle	91.2% [27]
				Middle East & North Africa	65.9% [13]		
				Sub-Saharan Africa	25.7% [8]	Lower middle	69.4% [15]
				Southern Asia	95.2% [3]		
				Eastern Europe & Central Asia	73.4% [21]	Low	27.1% [5]
				East Asia & Pacific	80.2% [10]		
Re-use	GWI [20] FAO [32]	Wastewater production normalised to reporting year of wastewater re-use based on GDP ($), percentage re-use calculated, applied to 2015 production data.	GWI data prioritised. FAO data if unavailable.	North America	90.0% [1]	High	68.7% [19]
				Latin America & Caribbean	67.2% [5]		
				Western Europe	42.5% [3]	Upper middle	77.7% [10]
				Middle East & North Africa	83.0% [13]		
				Sub-Saharan Africa	21.5% [6]	Lower middle	48.7% [4]
				Southern Asia	74.9% [1]		
				Eastern Europe & Central Asia	0.6% [2]	Low	24.8% [4]

* Abbreviations for the data sources are as follows: Global Water Intelligence (GWI), Food and Agricultural Organisation of the United Nations (FAO), United Nations Statistics Department (UNSD), European Union Statistics Office (Eurostat).~~ The number of countries per data source is displayed in square brackets.~~

**Data availability per region expressed as a percentage of the total population~~, with the number of countries in square brackets~~. Total number of countries per geographic region are: East Asia and Pacific [38], Eastern Europe and Central Asia [30], Latin America and Caribbean [41], Middle East and North Africa [21], North America [3], Southern Asia [8], Sub-Saharan Africa [48] and Western Europe [26].

***Data availability per economic classification expressed as a percentage of the total population~~, with the number of countries in square brackets~~. Total number of countries per economic classification are: High [76], Upper middle [56], Lower middle [52], and Low [31] income.

2.2 Regression for country-level predictions

Datasets of predictor variables for regression analyses were downloaded from multiple sources (see overview Table 2). Datasets spanned a wide range of predictor variables covering social (e.g. total and urban population), economic (e.g. GDP, HDI~~Human Development Index~~), hydrological (e.g. irrigation water scarcity) and geographic (e.g. land area, agricultural land) dimensions. The selected predictor variables were expected to have a physical basis for correlation with wastewater production, collection, treatment or re-use. Where appropriate, datasets from these sources were combined to produce comparable metrics for countries of different population and geographic sizes (e.g. GDP per ~~C~~capita [$ per capita]; desalination capacity per capita [m^3 yr^{-1} per capita]). Values were taken for the year 2015, where available, or from the closest reporting year when unavailable. Irrigation water scarcity and desalination capacity were taken from 2019 and 2018, respectively. Data was transformed, either using a log or square root transformation, to reduce the skew in the independent variables and to ensure normality.

Table 2. Data sources of predictor variables for wastewater production, collection, treatment and re-use regression analysis.

Data Source	Predictor Variable	Year	Link
World Bank	Land area (km^2)	2015	https://data.worldbank.org/indicator/AG.LND.TOTL.K2
	Total population (millions)	2015	https://data.worldbank.org/indicator/sp.pop.totl
	Urban population (%)	2015	https://data.worldbank.org/indicator/SP.URB.TOTL
	GDP (billion US$)	2015	https://data.worldbank.org/indicator/NY.GDP.MKTP.CD
	Access to basic sanitation (%)	2015	https://data.worldbank.org/indicator/SH.STA.BASS.ZS
	Mortality rate attributed to unsafe WASH	2015	https://data.worldbank.org/indicator/SH.STA.WASH.P5
	Access to internet (%)	2015	https://data.worldbank.org/indicator/it.net.user.zs
	Access to electricity (%)	2015	https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS
	People practicing open defecation (%)	2015	https://data.worldbank.org/indicator/SH.STA.ODFC.ZS
	Agricultural ~~L~~land (%)	2015	https://data.worldbank.org/indicator/AG.LND.AGRI.ZS
	Fertilizer consumption (kg /ha arable land)	2015	https://data.worldbank.org/indicator/ag.con.fert.zs
	Renewable internal water resources (billion m^3)	2015	https://data.worldbank.org/indicator/ER.H2O.INTR.K3
United Nations Development Programme	Human Development Index (-)	2015	https://dasl.datadescription.com/datafile/hdi-2015/
World Resources Institute	Baseline Irrigation Water Scarcity (-)	2019	https://www.wri.org/resources/data-sets/aqueduct-30-country-rankings
Global Water Intelligence	Desalination capacity (million m^3 yr^{-1})	2018	https://www.desaldata.com/ as synthesised in Jones et al. (2019)

Multiple linear regression was used to predict country-level wastewater variables (production, collection, treatment and re-use) for countries without reported data. Stepwise elimination was used for feature selection to remove redundant predictor variables and reduce overfitting. Wastewater production was predicted in volumetric flow rate units (million m^3 yr^{-1}). Conversely, wastewater collection, treatment and re-use were predicted as a percentage of wastewater production. Predicted values of percentages were bounded to the 0 – 100% range (i.e. <0 = 0; >100 = 100). Predicted percentages were subsequently applied to reported or predicted values of wastewater production to obtain wastewater collection, treatment and re-use in volumetric flow rate units. Bootstrap regression was used to quantify the uncertainty in the predictions (by geographic region, economic classification and at the global scale) at the 95th confidence level. In total, 1,000 regressions with random sampling and replacement were fit to provide predictions at countries lacking data. Wastewater observations were combined with these 1,000 bootstrapped predictions, with the 2.5th and 97.5th confidence intervals taken as lower and upper confidence limits, respectively.

Wastewater data (reported and predicted) are at the national level, for the 215 countries as listed by the World Bank (https://data.worldbank.org/country). Wastewater data are also aggregated to eight geographic regions based on the World Bank regional classifications: 1) East Asia & Pacific; 2) Eastern Europe & Central Asia; 3) Latin America & Caribbean; 4) Middle East & North Africa; 5) North America; 6) Southern Asia; 7) Sub-Saharan Africa; and 8) Western Europe. Furthermore, data areis also aggregated to four economic classifications based on the World Bank Atlas Method: 1) High income (>$12,056 GNI per capita); 2) Upper middle income ($3896 to $12,055); 3) Lower middle income ($966 to $3895); and 4) Low income (<$995). Predicted wastewater data was used to supplement reported data, where unavailable, to develop a comprehensive global outlook of wastewater production, collection, treatment and re-use.

2.3 Downscaling and validation

Country-level wastewater production, collection, treatment and re-use data was downscaled to 5 arc-minute resolution (~10km at the equator) based on the sum of averaged annual domestic and industrial return flow data (henceforth 'return flow'). Return flows represent the water extracted for a specific sectoral purpose, but is not consumed, and hence returns to and dynamically interacts with surface and ground water hydrology (de Graaf et al., 2014;Sutanudjaja et al., 2018). Return flows used for downscaling are calculated as gross - net water demands from the Water Futures and Solutions (WFaS) initiative for the years 2000 – 2010 (Wada et al., 2016). The WFaS water demand dataset follows the approach developed for PCR-GLOBWB (Wada et al., 2014). Domestic return flows only occurs where the urban and rural population have access to water, whereas industrial return flow occurs from all areas where water is withdrawn (Wada et al., 2014). Both domestic and industrial return flows are dependent on country-specific recycling ratios based on GDP and the level of economic development (Wada et al., 2011;Wada et al., 2014).

Grid cell return flow was divided by the country's total return flow to obtain the fraction per grid cell. Wastewater production was downscaled directly proportionally to return flows by multiplying the grid cell return flow fraction per grid cell with wastewater production at the country-level. Wastewater collection is assigned sequentially to grid cells with the largest downscaled produced wastewater flows. Thus, collected wastewater is preferentially allocated to grid cells with the highest levels of municipal activities, where central wastewater collection (and treatment) is assumed to be most economically feasible. Wastewater treatment is assigned to grid cells only where wastewater collection exists, at an average treatment rate calculated at the country-level. The treatment rate is calculated as the proportion of collected wastewater that undergoes treatment, and hence can differ from the country-level wastewater treatment percentage (which is calculated as the proportion of produced wastewater that is treated). For the downscaling of wastewater re-use an additional criterion was introduced to represent water scarcity, a key driver of wastewater re-use. The ratio of water demand to water availability was calculated. Grid cells within a country with a treated wastewater allocation are then ordered based off this ratio and treated wastewater re-use was assigned sequentially to these grid cells.

The location and design capacity of individual wastewater treatment plants were used to validate the downscaled wastewater treatment data. Reported data for 25,901 wastewater treatment plants located across Europe were obtained from the European Environmental Agency (EEA, 2019). Data for a further 4,283 wastewater treatment plants was obtained for the contiguous United States from the US Environmental Protection Agency (US-EPA, 2020). An additional 478 wastewater treatment plants, distributed globally (excluding Europe and the US), were extracted from the GWI wastewater database (GWI, 2015). For EEA and GWI wastewater treatment plants, treatment capacity reported only in Population Equivalent (PE) was approximated in volume flow rate units based on the linear regression obtained for wastewater treatment plants reporting ~~both~~ capacity in both population equivalent and volume flow rate (EEA: $R^2 = 0.80$, $p < 0.001$; GWI: $R^2 = 0.81$, $p < 0.001$). Wastewater treatment plants were assigned to their nearest grid cell and treatment capacities were aggregated per cell. In total, wastewater treatment data was available for 22,133 unique grid cells. For validating downscaled wastewater re-use, only plants (with treatment capacity > 1 million m^3 yr^{-1}) using tertiary or higher wastewater treatment technologies were considered. In total, 572 wastewater treatment plants in the EEA database met this criterion. A further 78 wastewater treatment plants, which are specifically designated as wastewater re-use facilities, were sourced from the GWI database. In total, wastewater re-use data was available for 601 grid cells. Downscaled wastewater treatment and re-use were~~as~~ compared to wastewater design capacities.

To account for the large variation in the treatment capacities of wastewater treatment plants considered, in addition to the geographical mismatch between where wastewater is produced and treated (i.e. wastewater treatment plants are typically located on the outskirts of urban areas), validation occurred at differing geographical scales. Wastewater treatment plant capacity was divided by wastewater production per capita to approximate the number of people that the wastewater treatment plant serves. If the population served by a wastewater plant exceeds the grid cell population, the validation extent ~~i~~was expanded to the directly neighbouring cells. This is allowed to occur until the population served by the treatment plant is reached, but up to a maximum of 3 iterations, reflecting a radius of ~30km around the wastewater treatment plant. The total downscaled wastewater treated over the extended area ~~i~~was then compared to that of the treatment plant.

To quantify the performance of the downscaling approaches, the root-mean-square error (RMSE) and mean bias (BIAS) were calculated. Normalised values of RMSE and BIAS were calculated (nRMSE and nBIAS) by dividing by the standard deviation of the wastewater treatment plant capacity. Pearson's (r) coefficients were~~as~~ calculated to quantify the linear dependence, with R^2 values based on both the linear and log-log relationship between downscaled and observed values also calculated.

3. Results

3.1 Regression and country-level predictions

Table 3. Wastewater production, collection, treatment and re-use multiple linear regression results.

Regression model	Explanatory Variables (units)	*B* (SE *B*)	β	P	Adjusted R^2
Production (log)	Intercept (-)	-1.68 (0.45)		**	0.89**
	GDP (log $ yr^{-1} per capita)	0.45 (0.06)	0.31	**	
	Population (log millions)	1.02 (0.03)	0.96	**	
	Access to basic sanitation (%)	0.02 (0.00)	0.19	**	
Collection	Intercept (-)	-80.73 (11.06)		**	0.69**
	Human ~~d~~Development ~~i~~Index (-)	120.82 (26.94)	0.50	**	
	Urban population (%)	0.22 (0.13)	0.14	.	
	Wastewater production (log m^3 yr^{-1} per capita)	8.01 (2.97)	0.25	*	
Treatment	Intercept (-)	-61.32 (14.06)		*	0.80**
	Wastewater collection (%)	0.72 (0.08)	0.66	*	
	GDP (log $ yr^{-1} per capita)	7.2 (1.88)	0.28	*	
Re-use (primary)	Intercept (-)	-5.29 (4.59)		0.26	0.70**
	Desalination capacity (sqrt m^3 yr^{-1} per capita)	1.50 (0.78)	0.29	.	
	Treated wastewater for irrigation water scarcity alleviation (-)	13.66 (3.50)	0.60	*	
Re-use (alternate)	Intercept (-)	-4.11 (6.10)		0.50	0.61**
	Desalination capacity (sqrt m^3 yr^{-1} per capita)	3.22 (0.63)	0.63	*	
	Treated wastewater (%)	0.23 (0.12)	0.24	.	

B indicates unstandardised regression weights, SE *B* indicates the standard error of *B*, β indicates standardised regression weights. Significance level represent by: '**' ($p<0.001$), '*' ($p<0.01$), '.' ($p<0.1$), or as stated numerically.

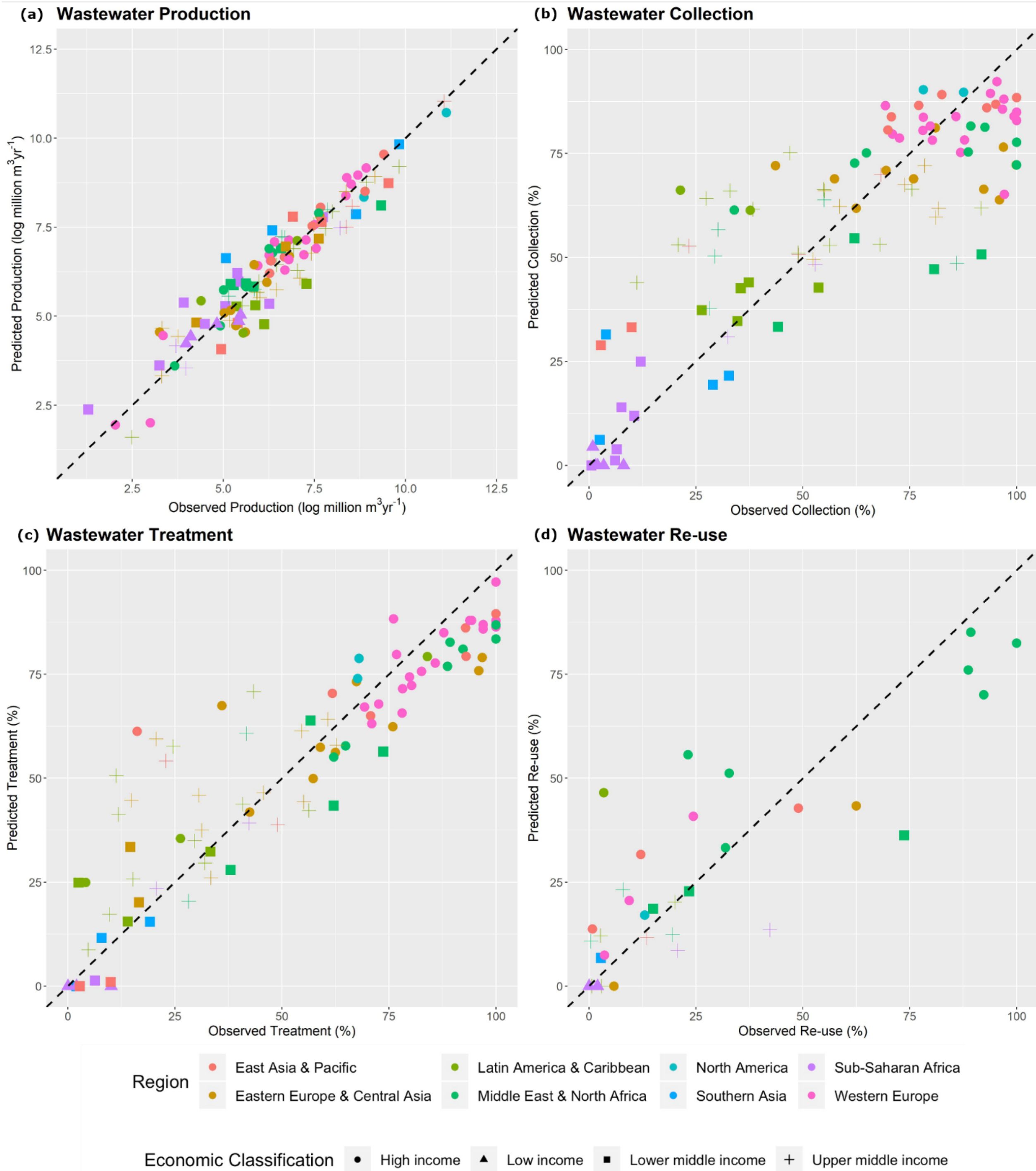
The results of the regression analysis for wastewater production, collection, treatment and re-use are summarised in Table 3. All regression models were significant at the $p<0.001$ level with adjusted R^2 values ranging between 0.61 and 0.89. Country-level observed versus simulated wastewater production (log million m^3 yr^{-1}), collection (%), treatment (%) and re-use (%) data are displayed in Figure 2. The regression equations were applied for 97, 113, 122 and 178 countries with no or excluded data representing 10%, 14%, 22% and 40% of the global population for wastewater production, collection, treatment and re-use, respectively.

Wastewater production was best predicted based on total population, GDP per capita and access to basic sanitation. A significant regression equation was found ($p<0.001$) with an adjusted R^2 value of 0.89, with all predictor variables also significant at the $p<0.001$ level. While~~st~~ the number of people within a country ~~is~~was found to have the strongest influence on~~ver~~ total wastewater production (β = 0.96), the average economic output per inhabitant (β = 0.31) and the level of access to wastewater services (β = 0.19), such as flushing toilets to piped sewers are important for determining the amount of wastewater produced per capita. These three factors therefore account for the combined effect of population size and variations in wastewater production per capita linked to economic and development factors in determining total wastewater production in a country. Comparing observed with predicted total wastewater production data demonstrates the overriding importance of a country's population, with wastewater production spread across multiple orders of magnitude for countries irrespective of geographical region or economic classification (Figure 2a).

Wastewater collection was predicted (adjusted $R^2 = 0.69$; $p < 0.001$) based on the hHuman dDevelopment iIndex (HDI), urban population and wastewater production per capita. HDI, an overarching proxy for level of development, was found to be the strongest influence over wastewater collection ($\beta = 0.50$; $p<0.001$). Urban population ($\beta = 0.14$; $p<0.01$) and wastewater production per capita ($\beta = 0.25$; $p<0.01$) were also significant but less important predictor variables of wastewater collection. For urban population, a greater proportion of a population living in urban areas resulted in higher collection rates for the country, while higher levels of wastewater production per capita corresponded to larger collection rates. The observed versus predicted wastewater collection rates are depicted in Figure 2b, which displays the trend across different geographic zones and economic classifications.

Wastewater treatment was predicted (adjusted $R^2 = 0.80$; $p < 0.001$) based on GDP per capita ($\beta = 0.28$; $p < 0.01$) and wastewater collection ($\beta = 0.66$; $p < 0.01$). Countries with larger economic outputs per capita likely have more resources for wastewater treatment, resulting in higher overall treatment rates. As wastewater treatment is dependent upon wastewater collection, countries with higher wastewater collection rates typically also treat a greater proportion of their wastewater. Observed versus predicted wastewater treatment rates are displayed in Figure 2c.

The amount of wastewater treated will determine the maximum potential for treated wastewater re-use within a country. Water scarcity, particularly when driven by high irrigation water demands, is also a primary driver of wastewater re-use (Garcia and Pargament, 2015). To account for this relationship, the fraction of wastewater undergoing treatment processes and irrigation water scarcity was multiplied to give an integrated metric indicating the 'availability of treated wastewater for irrigation water scarcity alleviation'. Wastewater re-use was predicted (adjusted $R^2 = 0.70$; $p < 0.001$) from this metric ($\beta = 0.60$; $p < 0.01$) in combination with the desalination capacity per capita ($\beta = 0.29$; $p < 0.1$), as an indicator of the prevalence of unconventional water resources in a country. The observed versus predicted wastewater re-use rates from this regression are displayed in Figure 2d. Irrigation water scarcity data was unavailable for 53 countries, mostly small island nations. Here an alternate regression model was constructed based on desalination capacity per capita ($\beta = 0.63$; $p < 0.01$) and wastewater treatment ($\beta = 0.24$; $p < 0.1$) only, resulting in a slightly lower explained variance ($R^2=0.61$). While these countries represent <1% of the global population, this alternate regression was necessary to account for wastewater re-use occurring particularly in water-scarce small island nations. These islands typically lack renewable water resources and hence unconventional water resources such as desalinated water and treated wastewater represent a substantialsignificant proportion of the water availability (Jones et al., 2019).


(a) Wastewater Production
Predicted Production (log million m3yr-1)
Observed Production (log million m3yr-1)
(b) Wastewater Collection
Predicted Collection (%)
Observed Collection (%)
(c) Wastewater Treatment
Predicted Treatment (%)
Observed Treatment (%)
(d) Wastewater Re-use
Predicted Re-use (%)
Observed Re-use (%)
Region
East Asia & Pacific
Eastern Europe & Central Asia
Latin America & Caribbean
Middle East & North Africa
North America
Southern Asia
Sub-Saharan Africa
Western Europe
Economic Classification
High income
Low income
Lower middle income
Upper middle income

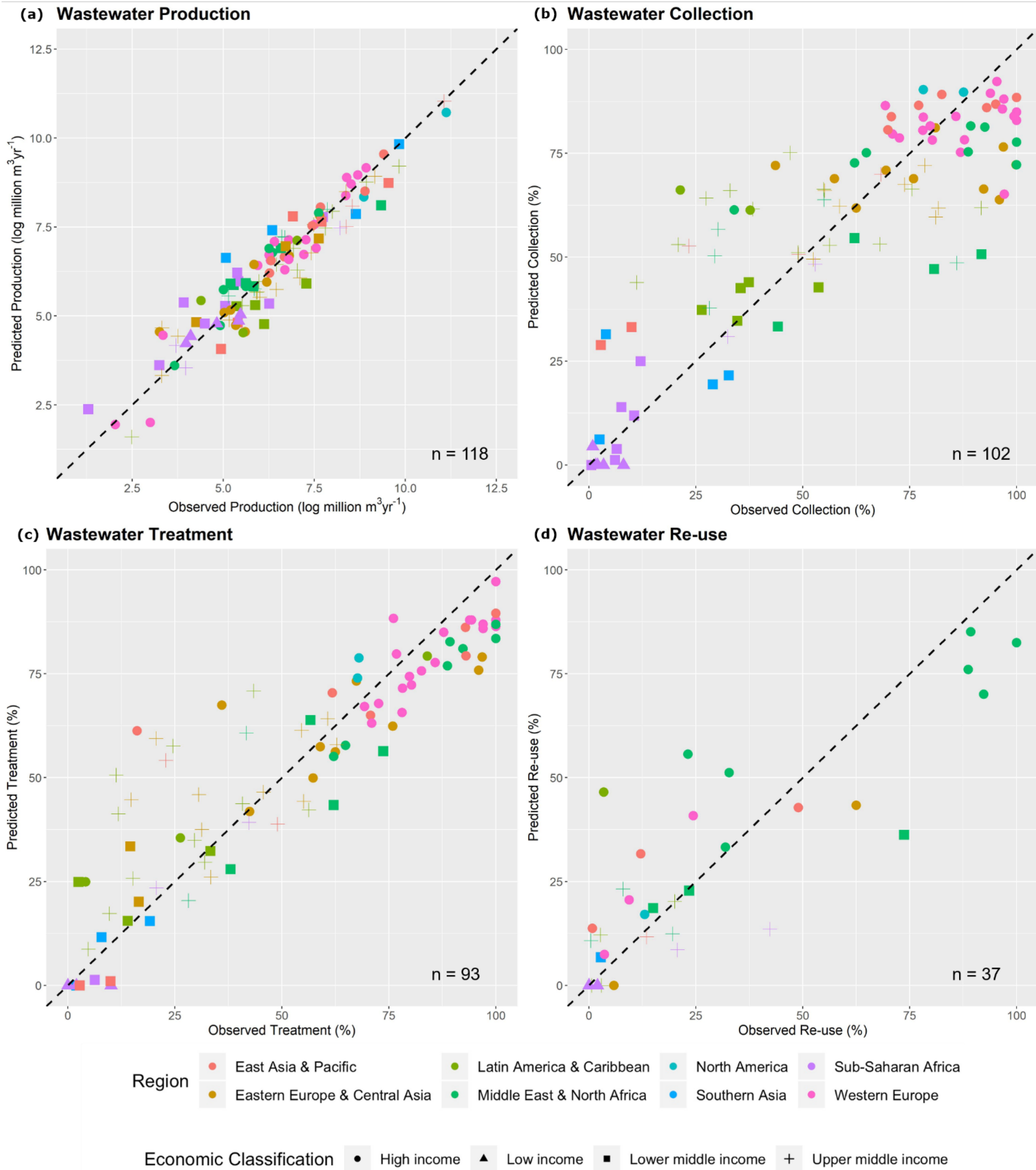

(a) Wastewater Production
Predicted Production (log million m3yr-1)
Observed Production (log million m3yr-1)
n = 118
(b) Wastewater Collection
Predicted Collection (%)
Observed Collection (%)
n = 102
(c) Wastewater Treatment
Predicted Treatment (%)
Observed Treatment (%)
n = 93
(d) Wastewater Re-use
Predicted Re-use (%)
Observed Re-use (%)
n = 37
Region
East Asia & Pacific
Eastern Europe & Central Asia
Latin America & Caribbean
Middle East & North Africa
North America
Southern Asia
Sub-Saharan Africa
Western Europe
Economic Classification
High income
Low income
Lower middle income
Upper middle income

Fig 2. Observed versus predicted wastewater production (a), collection (b), treatment (c) and re-use (d) from regression analysis.

3.2 Global wastewater production, collection, treatment and re-use

Globally, this study estimates that 359.4 (358.0 – 361.4) billion m^3 of wastewater is produced annually, with a global average of 49.0 (48.8 – 49.2) m^3 yr^{-1} per capita. Global wastewater collection and treatment is estimated at 225.6 (224.4 – 226.9) and 188.1 (186.6 – 189.3) billion m^3 yr^{-1}, respectively. These values indicate that approximately 63% and 52% of globally produced wastewater is collected and treated, respectively, with approximately 84% of collected wastewater undergoing a treatment process. Wastewater re-use is estimated at 40.7 billion (37.2 – 47.0) billion m^3 yr^{-1}, representing approximately 11% of the total volume of wastewater produced. This estimate also indicates that approximately 22% of treated wastewater undergoes intentional re-use, with the remaining 78% (totalling 147.4 billion m^3 yr^{-1}) discharged to the environment. This compares to the estimated 171.3 billion m^3 yr^{-1} of wastewater discharged directly to the environment without undergoing any form of treatment. It is worth highlighting that the vast majority of wastewater data areis from reported sources, with just 2.4%, 4.8% and 5.2% of global wastewater production, collection and treatment being from predicted values using regression. This occurs both due to the high population coverage and due to the missing data primarily being from developing countries nations, where wastewater production per capita and percentage collection and treatment rates are lower. The global quantification of wastewater re-use relies more heavily on predicted values, constituting 23.4% of re-use volume globally. This occurs primarily due to poor data availability, particularly in countries with large populations in Eastern Europe and Central Asia (e.g. Russia, Turkey and Poland) and Western European countriesnations where wastewater treatment rates are generally high but the proportion of wastewater re-used relies on simulations (e.g. Germany, Italy and Greece).

Table 4 displays wastewater production per capita (m^3 yr^{-1} per capita) and wastewater production, collection, treatment and re-use (billion m^3 yr^{-1}), aggregated from the country data (reported + simulated) at the global scale and by region and level of economic development. Figure 3 displays wastewater data plotted at the country scale in proportional terms (m^3 yr^{-1} per capita for production; percentage of produced wastewater for collection, treatment and re-use), facilitating direct comparisons between countries.

Substantial differences in wastewater production, collection, treatment and re-use occur across different geographic regions and by the level of economic development. Wastewater production per capita is notably highest in North America at 209.5 m^3 yr^{-1} per capita, over double that of Western Europe (91.7 m^3 yr^{-1} per capita), the next highest producing region per capita. When considering individual countries in these regions, the USA (211 m^3 yr^{-1} per capita) and Canada (198 m^3 yr^{-1} per capita), in addition to small, prosperous European countries (e.g. Andorra: 257 m^3 yr^{-1} per capita; Austria: 220 m^3 yr^{-1} per capita; Monaco: 203 m^3 yr^{-1} per capita) are the highest producers per Ccapita. Comparatively, the larger Western European countries have lower wastewater production per capita, with Germany, the U.K. and France at 92, 92 and 66 m^3 yr^{-1} per capita, respectively.

Conversely, most Sub-Saharan African countries~~nations~~ produce less than 10 m^3 yr^{-1} per capita. Wastewater production values are comparable to the World Health Organisation’s absolute minimum water requirements for survival of 2.7 m^3 yr^{-1} per capita (WHO, 2011) in countries such as Niger (2.7 m^3 yr^{-1} per capita), Burkina Faso (3.4 m^3 yr^{-1}) and Ethiopia (4.2 m^3 yr^{-1} per capita). Aggregated for the region, Sub-Saharan Africa produces approximately 20 times less wastewater than North America per capita, at 11.0 m^3 yr^{-1} per capita.

In volumetric flow rate terms, East Asia and Pacific produces the most wastewater (117.6 billion m^3 yr^{-1}), coinciding with the largest population share (~31%). Conversely, Southern Asia produces just ~7% of global wastewater despite a population share of ~24%, whereas the ~5% of people living in North America account for ~20% of global wastewater production. Wastewater production also varies greatly with level of economic development. The prominent discrepancies between economic classifications indicate~~s~~ a strong relationship between wealth and wastewater production regardless of geographic location. Wastewater production per capita more than doubles at each income classification level from low income (6.4 m^3 yr^{-1} per capita) to high income (126.0 m^3 yr^{-1} per capita). With respect to population size, people living in high income countries (~16% global population) produce ~42% of global wastewater, compared to low and lower-middle income countries (~50% global population) producing ~20% of global wastewater.

Wastewater collection and treatment rates are highest in Western Europe (88% and 86%, respectively) and lowest in Southern Asia (31% and 16%, respectively) and Sub-Saharan Africa (23% and 16%, respectively). Wastewater collection is notably low in the East Asia and Pacific region, where total wastewater production is high. Conversely, wastewater collection in the Middle East and North Africa region is relatively high at 74%, likely resulting from the lack of renewable water supplies. Wastewater treatment percentages follow similar regional patterns. Notably, wastewater treatment is substantially~~significantly~~ lower than wastewater collection in the Latin America and Caribbean and Southern Asia regions, potentially indicative of high rates of untreated wastewater re-use in these regions. Wastewater collection and treatment percentages follow similar patterns as wastewater production with respect to income level, with high income countries collecting and treating the majority of their wastewater (82% and 74%, respectively) down to low income countries with small collection and treatment rates (9% and 4%, respectively). The proportion of collected wastewater being treated also decreases with income level, at 91%, 73%, 60% and 47% for high, upper middle, lower middle and low income classifications, respectively. The fact that 40% and 53% of collected wastewater is untreated in the lower middle and low income classifications, ~~-~~respectively, may also be indicative of the higher prevalence of intentional untreated wastewater re-use (whereby collected wastewater is re-used without undergoing treatment).

High utilisation of treated wastewater re-use occurs predominantly in the Middle East and North Africa, with the United Arab Emirates, Kuwait and Qatar re-using more than 80% of their produced wastewater. Water scarce small island developed countries~~nations~~, including the Cayman Islands, US Virgin Islands and Malta also have high rates of intentional treated wastewater re-use of 78%, 75% and 67%, respectively. Treated wastewater re-use is prohibitively low in areas with low wastewater treatment rates, such as Sub-Saharan Africa and Southern Asia. In addition, treated wastewater re-use is also low in areas with sufficient availability of conventional water resources such as across Scandinavia (where re-use is <5%).

In volumetric flow rate terms, intentional treated wastewater re-use is estimated to be largest in East Asia & Pacific (11.9 billion m^3 yr^{-1}) and North America (9.1 billion m^3 yr^{-1}) and lowest in Southern Asia (0.5 billion m^3 yr^{-1}) and Sub-Saharan Africa (1.6 billion m^3 yr^{-1}). Conversely the Middle East & North Africa (27.8%) and Western Europe (17.5%) ~~regions~~ dominate in percentage terms. In volumetric flow rate units, the Middle East & North Africa (15%) and Western Europe (16%) account for almost a third of treated wastewater re-use globally, despite only accounting for 5.8% and 5.7% of the global population, respectively. Approximately half (52%) of intentional treated wastewater re-use occurs in high income countries, with 37% from upper middle income countries. Intentional treated wastewater re-use is contingent upon the availability of treated wastewater resources, which is typically more prevalent in high income countries (who both produce more wastewater per capita and treat~~ed~~ a higher percentage of the resource). However, the proportion of treated wastewater intentionally re-used is higher in the upper middle (25%) and lower middle (25%) income groups than ~~by~~in the high income group (19%).

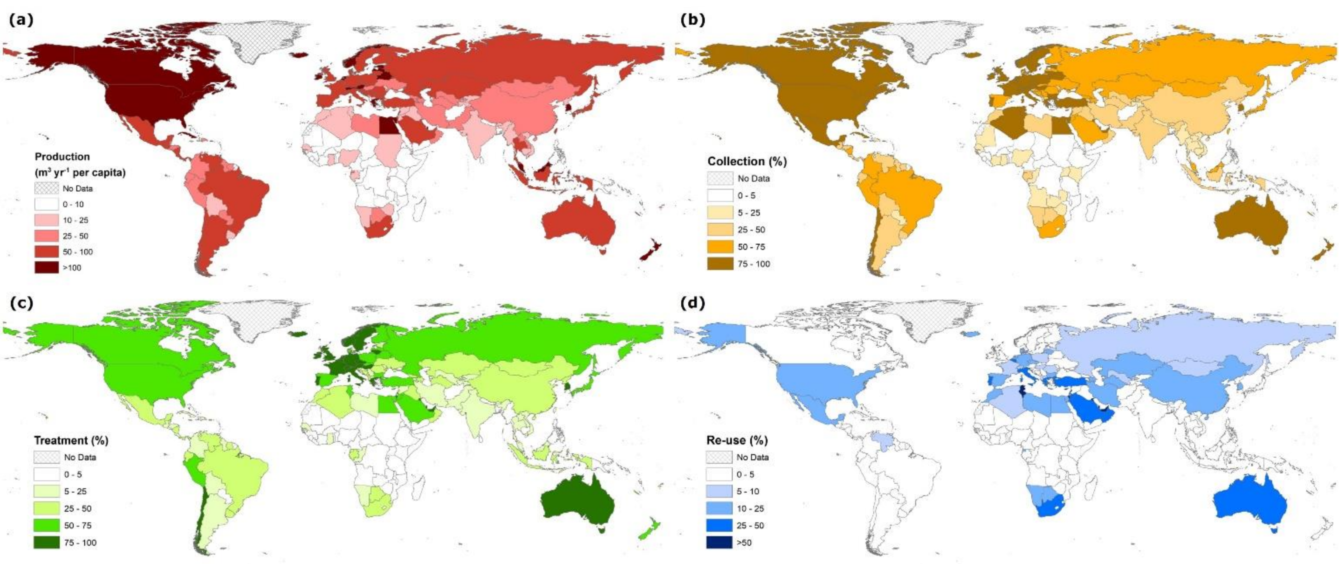


Fig 3. Wastewater production (m^3 yr^{-1} per capita) (a), collection (%) (b), treatment (%) (c) and re-use (%) (d) at the country scale.

Table 4. ~~Global, regional and level of economic development analysis of w~~Wastewater production, collection, treatment and re-use (billion m^3 yr^{-1}) by region and level of economic development. The numbers in parentheses~~brackets~~ display the prediction uncertainty (2.5th and 97.5th confidence limits, in billion m^3 yr^{-1}) on the totals based on the results of 1,000 bootstrap regressions with random sampling and replacement.

	Global Population (%)	**Production (m^3 yr^{-1} per capita)**	**Production (billion m^3 yr^{-1})**	**Collection (billion m^3 yr^{-1})**	**Treatment (billion m^3 yr^{-1})**	**Re-use (billion m^3 yr^{-1})**
Global	100	49.0 *(48.8 – 49.2)*	359.4 *(358.0 – 361.4)*	225.6 *(224.4 – 226.9)*	188.1 *(186.6 – 189.3)*	40.7 *(37.2 – 47.0)*
Geographic Region						
North America	4.9	209.5 *(209.5 - 209.5)*	74.7 *(74.7 – 74.7)*	59.1 *(59.1 – 59.1)*	50.6 *(50.6 – 50.6)*	9.1 *(8.8 – 9.5)*
Latin America & Caribbean	8.5	67.6 *(67.3 – 67.9)*	42.1 *(41.9 – 42.3)*	25.2 *(25.2 – 25.2)*	15.4 *(15.2 – 15.5)*	2.1 *(2.0 – 2.5)*
Western Europe	5.7	91.7 *(91.7 – 91.8)*	38.5 *(38.4 – 38.5)*	33.7 *(33.7 – 33.7)*	33.0 *(33.0 – 33.0)*	6.7 *(4.1 – 9.5)*
Middle East & North Africa	5.8	51.4 *(51.3 – 51.5)*	21.9 *(21.8 – 21.9)*	16.1 *(16.1 – 16.2)*	11.4 *(11.2 – 11.5)*	6.1 *(6.0 – 6.2)*
Sub-Saharan Africa	13.6	11.0 *(10.1 – 12.4)*	11.0 *(10.1 – 12.4)*	2.5 *(2.5 – 2.6)*	1.8 *(1.7 – 1.9)*	1.6 *(1.6 – 1.8)*
Southern Asia	23.8	14.6 *(14.5 – 14.7)*	25.6 *(25.4 – 25.7)*	7.8 *(7.8 – 7.8)*	4.0 *(4.0 – 4.1)*	0.5 *(0.5 – 0.8)*
Eastern Europe & Central Asia	6.6	57.9 *(57.2 – 58.8)*	28.2 *(27.8 – 28.6)*	18.4 *(18.2 – 18.7)*	14.9 *(14.7 – 15.1)*	2.6 *(1.3 – 4.4)*
East Asia & Pacific	31.1	51.5 *(51.5 – 51.7)*	117.6 *(117.3 – 117.9)*	62.8 *(61.9 – 63.8)*	57.0 *(56.1 – 57.8)*	11.9 *(11.7 – 13.5)*
Economic Classification						
High	16.1	126.0 *(125.9 – 126.2)*	149.1 *(149.0 – 149.3)*	121.7 *(121.6 – 121.7)*	110.4 *(110.4 – 110.5)*	21.2 *(19.1 – 24.9)*
Upper middle	34.8	54.7 *(54.5 – 54.8)*	139.5 *(139.1 – 139.9)*	74.8 *(74.6 – 74.9)*	60.2 *(59.7 – 60.6)*	15.1 *(13.9 – 16.9)*
Lower middle	40.5	22.5 *(22.3 – 22.6)*	66.8 *(66.4 – 67.4)*	28.8 *(27.7 – 29.9)*	17.3 *(16.2 – 18.2)*	4.4 *(3.6 – 5.7)*
Low	8.6	6.4 *(5.0 – 8.5)*	4.0 *(3.2 – 5.3)*	0.4 *(0.3 – 0.4)*	0.2 *(0.1 – 0.2)*	0.0 *(0.0 – 0.1)*

3.3 Gridded wastewater production, collection, treatment and re-use

Figure 4 displays gridded wastewater production, collection, treatment and re-use, allowing for the identification of hotspot regions and zones at 5 arc-min resolution. Wastewater production occurs across the globe, with hotspots coinciding with the largest metropolitan areas (e.g. Tokyo and Mumbai) where the largest concentration of domestic and industrial activities occurs (Figure 4a). In contrast, wastewater production is close to zero in world regions with low concentrations of people and industrial activities, such as the Sahara desert, inland Australia and the high latitude climate zones (e.g. Northern Canada and Russia). In countries where municipal activities are heavily concentrated in a small number of cities, such as in the Middle East and Australia, small clusters of grid cells with very high wastewater production (>5 million m^3~~/~~ $year^{-1}$) occur~~s~~. Wastewater collection (Figure 4b) and treatment (Figure 4c) are~~is~~ typically more concentrated in urban areas within individual countries. This is particularly prominent in South America and Sub-Saharan Africa. Conversely, downscaled wastewater collection and treatment reflect wastewater production in regions where wastewater collection and treatment rates are very high, such as Western Europe and Scandinavia. Wastewater re-use is constrained to the lowest area (number of grid cells), being concentrated in regions with~~ only~~ -where ~~available~~treated wastewater resources are available and where ~~-conditions of~~ water scarcity issues are of particular concern.

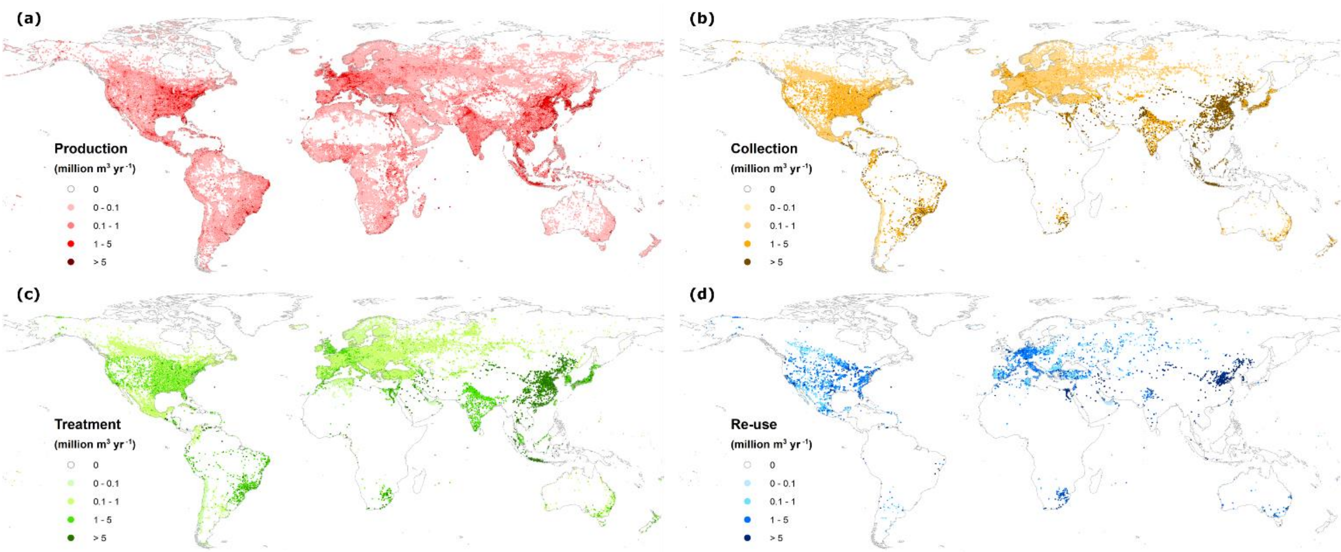


Fig 4. Gridded wastewater production (a), collection (b), treatment (c) and re-use (d) (million m^3 yr^{-1}) at 5 arc-minute spatial resolution.

Figure 5a displays the global distribution of the wastewater treatment plants and designated wastewater re-use sites considered in this study. Plant capacities were compared to downscaled quantifications for validation of wastewater treatment (Figure 5b) and wastewater re-use (Figure 5c). Overall, a reasonable performance is obtained at most wastewater treatment and re-use plants with linear R^2 values of 0.57 ($p < 0.001$) and 0.50 ($p < 0.001$), respectively. The observed negative normalised biases suggest that downscaled wastewater treatment (-0.32) and re-use (-0.51) was underestimated with respect to the observed treatment capacities. This may occur due to discrepancies between the design (i.e. maximum) capacity of wastewater treatment plants, which is commonly the capacity that is reported, versus the actual treated wastewater volumes. Factors such as the construction year of wastewater treatment plant are important, as plants are constructed to be larger than current requirements in anticipation of future increases in wastewater flows. Furthermore, uncertainties in the data used as basis for downscaling wastewater production (i.e. PCR-GLOBWB return flows) directly impacts the downscaled results of wastewater treatment. For example, the underprediction of return flows in urban areas and overprediction in rural areas could lead to the overprediction of wastewater treatment in areas without treatment plants and underprediction of wastewater treatment for grid cells with large treatment capacities.

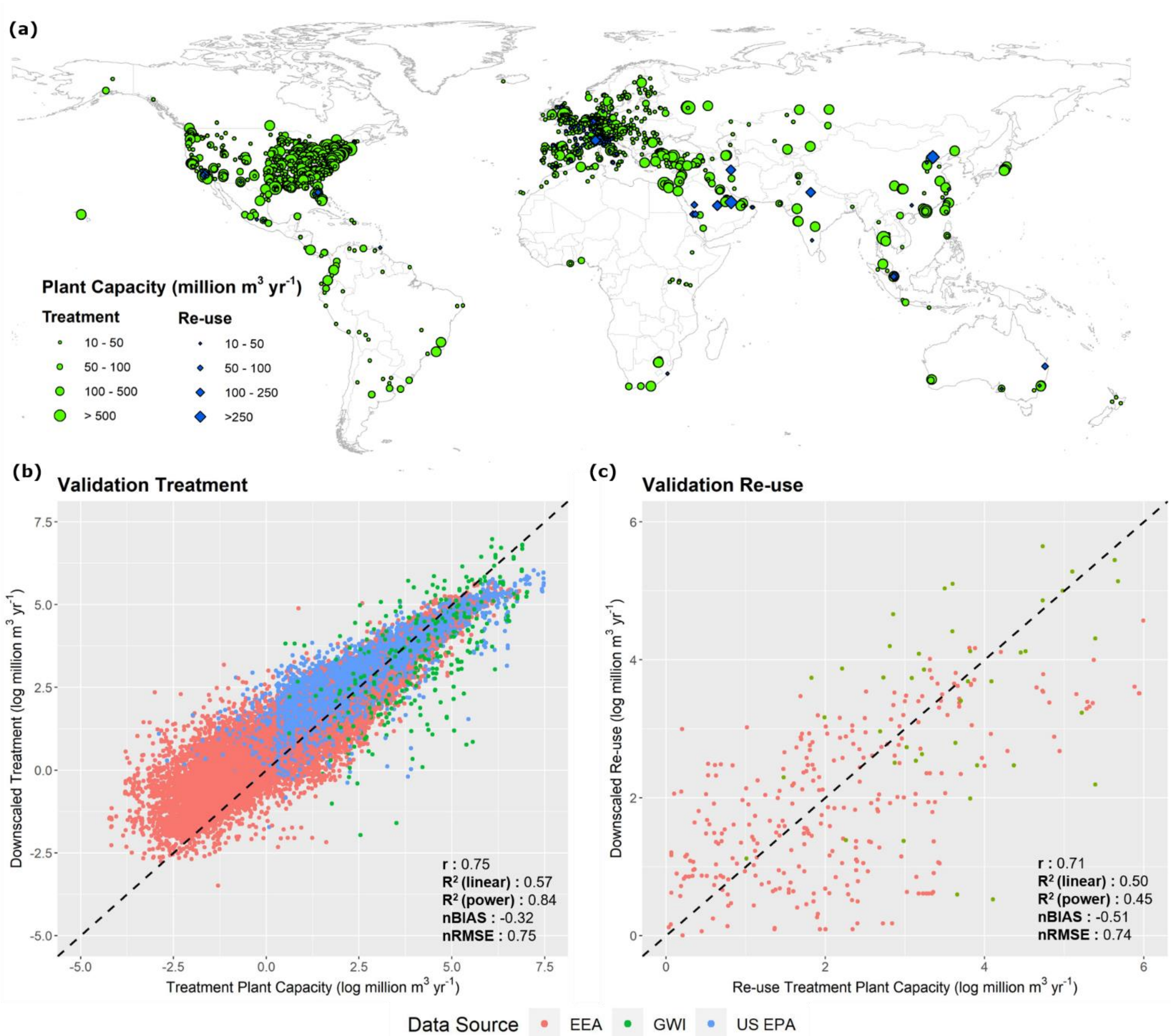


Fig 5. Global distribution of wastewater treatment plants and designated wastewater re-use sites (a), and validation of downscaling approach for wastewater treatment (b) and wastewater re-use (c).

4. Data availability

The country-level and spatially-explicit (5 arc-minutes) wastewater production, collection, treatment and re-use datasets at 5 arc-minutes can be accessed at: https://doi.pangaea.de/10.1594/PANGAEA.918731 (Jones et al., 2020). A temporary link to this dataset for the review process can be accessed at: https://www.pangaea.de/tok/6631ef8746b59999071fa2e692fbc492c97352aa.

5. Discussion and conclusions

This study aimed to develop a consistent and comprehensive spatially-explicit assessment of global domestic and industrial wastewater production, collection, treatment and re-use for the reference year of 2015. Multiple linear regression models using a diverse set of social, economic, geographic and hydrological datasets were fit for country-level wastewater data collated for a variety of sources. These relationships applied for predictions of wastewater production, collection, treatment and re-use for countries where data was unavailable. Bootstrapping with random sampling and replacement was employed to quantify prediction uncertainty. It should be noted that bootstrapping only accounts for uncertainty in the regression terms, not for uncertainties in the underpinninglying source data. Uncertainties associated with wastewater observations are not accounted for in this study, despite likely being substantial. Nevertheless, this study represents the first attempt to simultaneously analyse wastewater production, collection, treatment and re-use for all countries across the globe. While agricultural runoff is also a substantial source of pollution, this is outside the scope of this study. Country-level data on agricultural runoff is sparse, necessitating modelling approaches to quantify irrigation return flow by calculating net demand (e.g. based on crop composition and irrigated area per grid cell), gross irrigation demand (to account for irrigation efficiency and losses) and water withdrawals (Sutanudjaja et al., 2018). Agricultural runoff is also rarely collected or treated (UNEP, 2016), hence is less applicable for inclusion in this study.

Our global quantification of wastewater production of 359.4 (358.0 – 361.4) billion m^3 yr^{-1} is broadly in accordance with previous quantifications, such as 380 billion m^3 yr^{-1} quantified based on reported data and urban population only (Qadir et al., 2020), and 450 billion m^3 yr^{-1} quantified by modelling of return flows in WaterGAP3 (Flörke et al., 2013). Few studies were found analysing the global state of wastewater collection, treatment and re-use. Our quantification of wastewater collection, which is estimated at 225.6 (224.4 – 226.9) billion m^3 yr^{-1}, can give an important indication of the amount of collected wastewater that goes untreated. At the global scale, this study estimates that wastewater treatment is 188.1 (186.6 – 189.3) billion m^3 yr^{-1}, or 52% of the produced wastewater. By extension, 48% of produced wastewater is released to the environment without treatment (either directly, or following collection). This is substantiallysignificantly lower than the commonly cited statistic that ~80% of global wastewater is released to the environment without treatment (WWAP, 2012; UN-Water 2015a; UNESCO, 2017). Our quantifications of wastewater treatment must be treated with caution however – particularly in the developing world – as wastewater treatment plants typically operate at capacities below the installed (and usually reported) capacities (Mateo-Sagasta et al., 2015;Murray and Drechsel, 2011) ~~upon which~~that are used for country-level estimates ~~incorporate~~. Similarly, wastewater plants may be entirely non-functional (mothballed) due to lack of funding and maintenance, or have unsuitable treatment processes for the incoming wastewater, yet the associated wastewater volumes are still reported as treated (Qadir et al., 2010). Therefore, it is possible that the actual treated volume of wastewater is somewhat below our estimated 52% and the proportion of collected wastewater which is not treated could far exceed 16%. ‘Wastewater treatment’ is also a generic term that may refer to any form of wastewater treatment regardless of level (e.g. primary, secondary or tertiary), which this study does not attempt to distinguish between. This is due to different data sources reporting different levels of treatment, for instance with GWI only reporting secondary treatment or above while~~st~~ FAO-AQUASTAT also includes primary treatment.

In percentage terms, wastewater treatment by economic classification is broadly in line with previous work (Sato et al., 2013), who estimate wastewater treatment to be 70%, 38%, 28% and 8% for high income, upper middle income, lower middle income and low income countries, respectively, compared to our quantifications of 74%, 43%, 26% and 4.2%. While~~st~~ similar, these estimations could potentially indicate that percentage collection and treatment have increased in the developed world, but have decreased in the developing world. This could be caused by wastewater production, particularly in the developing world, rising at a faster pace than the development of collection infrastructure and treatment facilities (Sato et al., 2013). It should be noted that while the aim of wastewater collection and treatment is to reduce pollutant loadings to minimise risks to human health and the environment, these facilities can also act as point sources of pollution. Wastewater collection concentrates pollutants which can pose serious water quality issues if discharged with insufficient treatment,. Furthermore, a range of emerging pollutants (e.g. pharmaceuticals, pesticides and industrial chemicals) are concentrated in wastewater collection networks (Geissen et al., 2015). These pollutants are of particular concern as they are not typically monitored for or sufficiently removed in wastewater treatment processes, with ambiguous risks posed to human and environmental health even in low concentrations (Deblonde et al., 2011;Geissen et al., 2015). The solution is not however to collect less wastewater, but to increase treatment in terms of percentage of collected wastewater, treatment level and the number of pollutants (UNEP, 2016).

The drivers behind wastewater re-use are a complex mixture of social, economic, geographic and hydrological ~~drivers~~factors, and data are~~is~~ highly limited globally. Nevertheless, this study represents the first attempt to quantify intentionally treated wastewater re-use at the country scale. It should be noted that this study does not aim to quantify either de-facto (unintentional) treated wastewater re-use or any form (intentional or unintentional) of untreated wastewater re-use. The total volume of wastewater re-used for human purposes is therefore likely much greater than the 40.7 billion $m^3 yr^{-1}$ of intentional treated wastewater re-use estimated in this study. For example, previous research has indicated that the magnitude of intentional untreated wastewater re-use may be approximately ten times greater than intentional treated wastewater re-use (Scott et al., 2010).

This study sought to downscale country-level wastewater estimates to spatially-explicit (grid-based) quantifications for purposes such as large-scale water resource assessments and water quality modelling. Wastewater production has previously been quantified based only on simulated return flows in hydrological models (Flörke et al., 2013). ~~Whilst our results also rely on this approach, w~~We instead used the proportions of simulated return flows to downscale ~~our~~ country-based volumes of wastewater production. Our results also represent the first efforts to quantify global wastewater collection, treatment and re-use at the sub-national level. Our validation results suggest that our downscaled estimates of wastewater treatment and re-use are, in general, realistic. However, a number of uncertainties should also be considered. Firstly, our downscaling for wastewater production inherently relies on the ability to accurately simulate domestic and industrial return flows, and hence on the methodology for calculating gross and net water demand (Wada et al., 2014). As we downscale using the return flows proportionally, accurate spatial disaggregation of return flows is more important than the absolute simulated flow volumes. The accuracy of downscaled wastewater collection relies on the assumption that this preferentially occurs in areas where wastewater production is highest. Due to the high capital costs of wastewater treatment plants, combined with economies of scale, we deem this a logical assumption (Hernández-Chover et al., 2018;Hernandez-Sancho et al., 2011). Lacking more detailed information on the spatial variance in wastewater collection compared to treatment, we assume an equal wastewater treatment rate across all cells that have a collected wastewater allocation. Wastewater re-use is downscaled with the only additional criteria being an indicator of water scarcity. While~~st~~ water scarcity is an important driver of wastewater re-use, site-specific social, economic and political factors will also have a large influence on the viability of wastewater re-use on a case-by-case basis (WWAP, 2017). Accounting for these factors is outside the scope of this study. Furthermore, uncertainties in the validation datasets, both in terms of treatment capacity and geographical location, must also be recognised. Overall, due to the global scale of this work and the available data for validation, we purposely opt for more simple and parsimonious approaches where possible.

This study did not target acreage in its considerations of wastewater re-use, which has been a common method in previous work. For example, estimates made a decade ago suggest that up to 200 million farmers practice wastewater irrigation over an area of 4.5 – 20.0 million ha worldwide (Jiménez and Asano, 2008;Raschid-Sally and Jayakody, 2008). More recently, a global, spatially explicit assessment of irrigated croplands influenced by municipal wastewater flows estimated the area under direct and indirect wastewater irrigation at 36 million ha, of which 29 million ha are likely exposed to untreated wastewater flows (Thebo et al., 2017). These estimates were based on modelling studies and considered wastewater in both diluted and undiluted forms with a cropping intensity of 1.48 (Thebo et al., 2014). Considering the same cropping intensity and recent estimates of wastewater production (380 billion m^3 yr^{-1}), the irrigation potential of undiluted wastewater was estimated at 42 million ha (Qadir et al., 2020).

Our results have a range of important applications including as input data for water resource assessments and ~~for~~ as a baseline for informing and evaluating economic and management policies related to wastewater. For example, our data can be used to assess progress towards SDG 6.3 aimed at halving the proportion of untreated wastewater discharged into water bodies. As our data is standardised for 2015 and provides full geographic coverage, problems of discrepancies in data reporting years and missing data are reduced~~overcome~~. Similarly, our data allows for identification of hotspot regions whereby the proportion of wastewater collected and treated are low, and of areas where large volumes of wastewater are entering the environment untreated (Figure 6). Volumetrically, substantial untreated wastewater flows to the environment are found ~~particularly~~ across South and Southeast Asia, particularly in the populous regions of Pakistan, Malaysia, Indonesia, India and China. Information on untreated wastewater flows have a diverse range of important implications for global water quality modelling and human health assessments.

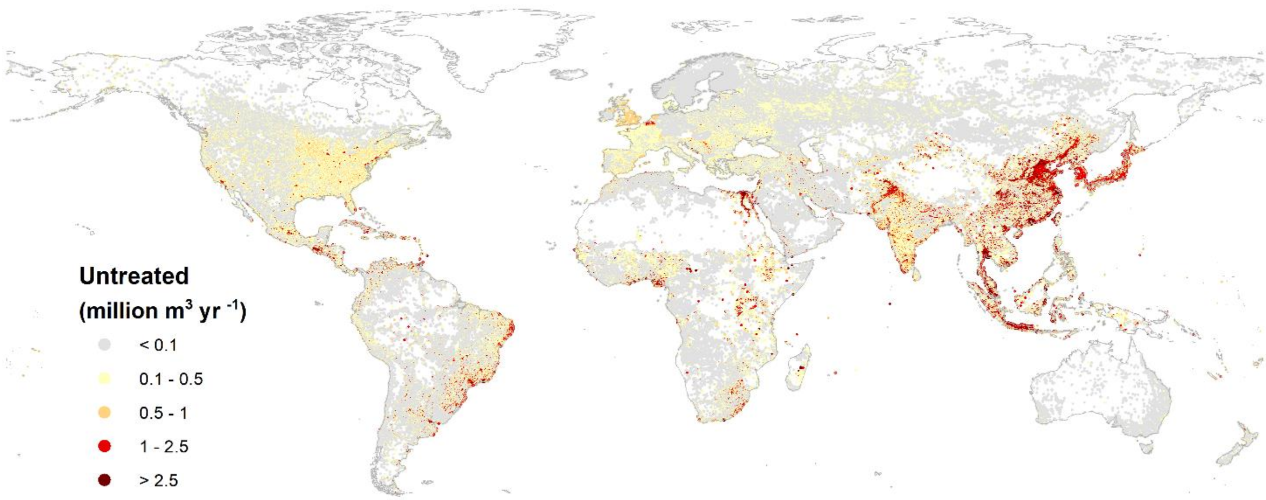


Figure 6. Gridded untreated wastewater flows to the environment (million m^3 yr^{-1}) at 5 arc-minute spatial resolution.

Our results also highlight the vast potential of treated wastewater as an unconventional water resource for augmenting water resources and alleviating water scarcity, particularly in water scarce regions. To put wastewater as a potential resource into perspective, its estimated global volume of ~360 km^3 year^{-1} is comparable to the global consumptive use of non-renewable groundwater of 150-400 km^3 year^{-1} over the years 2000-2010 (Bierkens and Wada, 2019). As wastewater production continues to rise with population and economic growth, wastewater management and re-use practices will become more important in the future (WWAP, 2017). Expansion in re-use of wastewater must be accompanied by strong legislation and regulations to ensure its safety (Smol et al., 2020;Voulvoulis, 2018). However, in response to concerns related to groundwater contamination, disruption to industrial processes and impacts for human health, tightening regulation can also be a barrier to expansion in treated wastewater re-use (Voulvoulis, 2018). It should also be recognised that wastewater re-use is not viable in all regions due to economic, technical and social considerations (Voulvoulis, 2018). Particularly in water-scarce developing countriesnations with economic constraints, the application of untreated wastewater (diluted or undiluted) will likely remain the dominant form of wastewater re-use (Qadir et al., 2010). This is especially true in dry areas, despite official restrictions and regardless of potential health implications, where untreated wastewater re-use is triggered because (1) wastewater is a reliable or often the only guaranteed water source available throughout the year; (2) the need to apply fertilisers decreases as wastewater is a source of nutrients; (3) wastewater re-use can be cheaper and less energy intensive than other water sources, such as if the alternative clean water source is deep groundwater; and (4) additional economic benefits such asincluding higher income generation from the cultivation and marketing of high-value crops such as vegetables, which can createing year-round employment opportunities.

Continued failure to address wastewater as a major social and environmental challenge prohibits progress towards the 2030 Agenda for Sustainable Development (WWAP, 2017). Ultimately, the cost of action must also be weighed against the cost of inaction (Hernández-Sancho et al., 2015). A paradigm shift in wastewater management is required from viewing wastewater as solely an environmental problem associated with pollution control and regulations, to recognise the economic opportunities of wastewater, which can provide a means of financing management and treatment (Wichelns et al., 2015;WWAP, 2017). In addition to revenue from selling treated wastewater for re-use, these opportunities include 'fit-for-purpose' treatment (Chhipi-Shrestha et al., 2017), recovery of energy and nutrients (Qadir et al., 2020) and cascading re-use of water from high to lower quality (Hansen et al., 2016). Creative exploitation of these opportunities offers potential to support the transition to a circular economy (Smol et al., 2020;Voulvoulis, 2018) and make progress towards many interconnected SDGs such as achieving a water-secure future for all (WWAP, 2017).

Author contribution

ERJ performed the analyses, drafted the manuscript and developed the study with input of MTHvV and MFPB. MTHvV, MQ and MFPB provided feedback and guidance throughout the entire process. All authors contributed to and approved the manuscript.

Competing interests

The authors declare no competing financial interests.

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